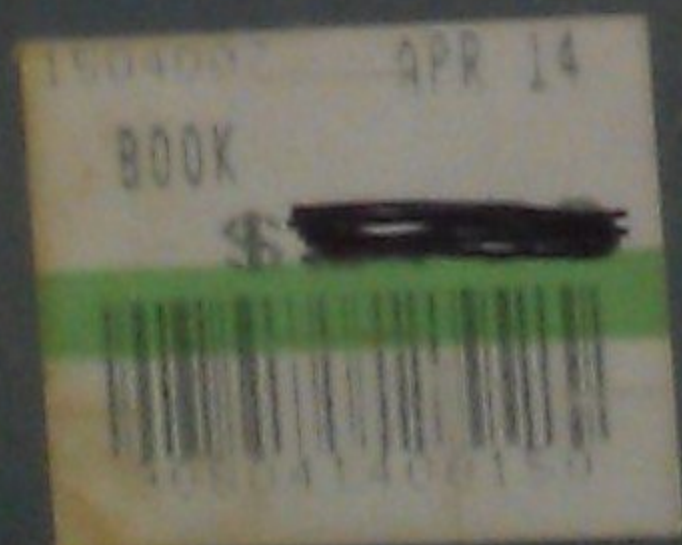


# **fundamentals of nuclear energy and power reactors**

by Henry Jacobowitz



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**fundamentals of  
nuclear energy  
and  
power reactors**

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## PREFACE

Just ten years after its inception on a commercial basis, nuclear energy is a growing industry. Valuable practical experience is being accumulated from a variety of reactor designs, and soon large-scale competitive nuclear power should be available. Therefore, some familiarity with the essentials of nuclear energy becomes a prerequisite to an understanding of the economic and scientific revolution of our era. This book is intended to explain nuclear energy fundamentals—both basic physical concepts and the practical applications. The presentation is made sufficiently readable to attract the general interested public, as well as the growing membership of the atomics industry.

The first two chapters are concerned with atomic and nuclear theory. Chapter 1 introduces the reader to some of the sophisticated quantum and wave-mechanical concepts of the atom that preceded the breakthrough in nuclear physics. Chapter 2 explores the nuclear reactions leading to fission and the conditions necessary for slow or fast chain reactions. The last two chapters of the book are devoted to nuclear reactors and power plants. The early types of research reactors, which represent a basic design reservoir for most practical power reactors, are described in Chapter 3. Chapter 4 considers the nuclear reactor in a larger setting, as the heart of a nuclear power plant. A roster of most of the existing and proposed nuclear plant

designs mentions each installation to some extent, if only to point out essential principles and differences from other designs. A few large-scale power plants are described in considerable detail.

The author would like to express his appreciation for the generous amount of information and illustrative material he received from the Technical Information Service of the Atomic Energy Commission, the Westinghouse Electric Corporation, the Brookhaven National Laboratory, and others noted within the book.

*New York, N.Y.*  
*January 1959*

HENRY JACOBOWITZ.

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To Hilda and Lisa

**"By convention sweet is sweet, by convention bitter is bitter, by convention hot is hot, by convention cold is cold, by convention color is color. But in reality there are atoms and the void. That is, the objects of sense are supposed to be real and it is customary to regard them as such, but in truth they are not. Only the atoms and the void are real."**

**Democritus, ca. 420 B.C.**

# 1: THE ATOM AND ITS NUCLEUS

## Atomic Theories

"Only the atoms and the void are real," Democritus said, and the sentence stands 2400 years later. If we have learned anything in the interval, it is to question the nature of these atoms, and even more fundamentally, the nature of reality. Atoms and the things they are thought to be made of—*electrons, protons and neutrons*—are variously described (see Fig. 1-1) as

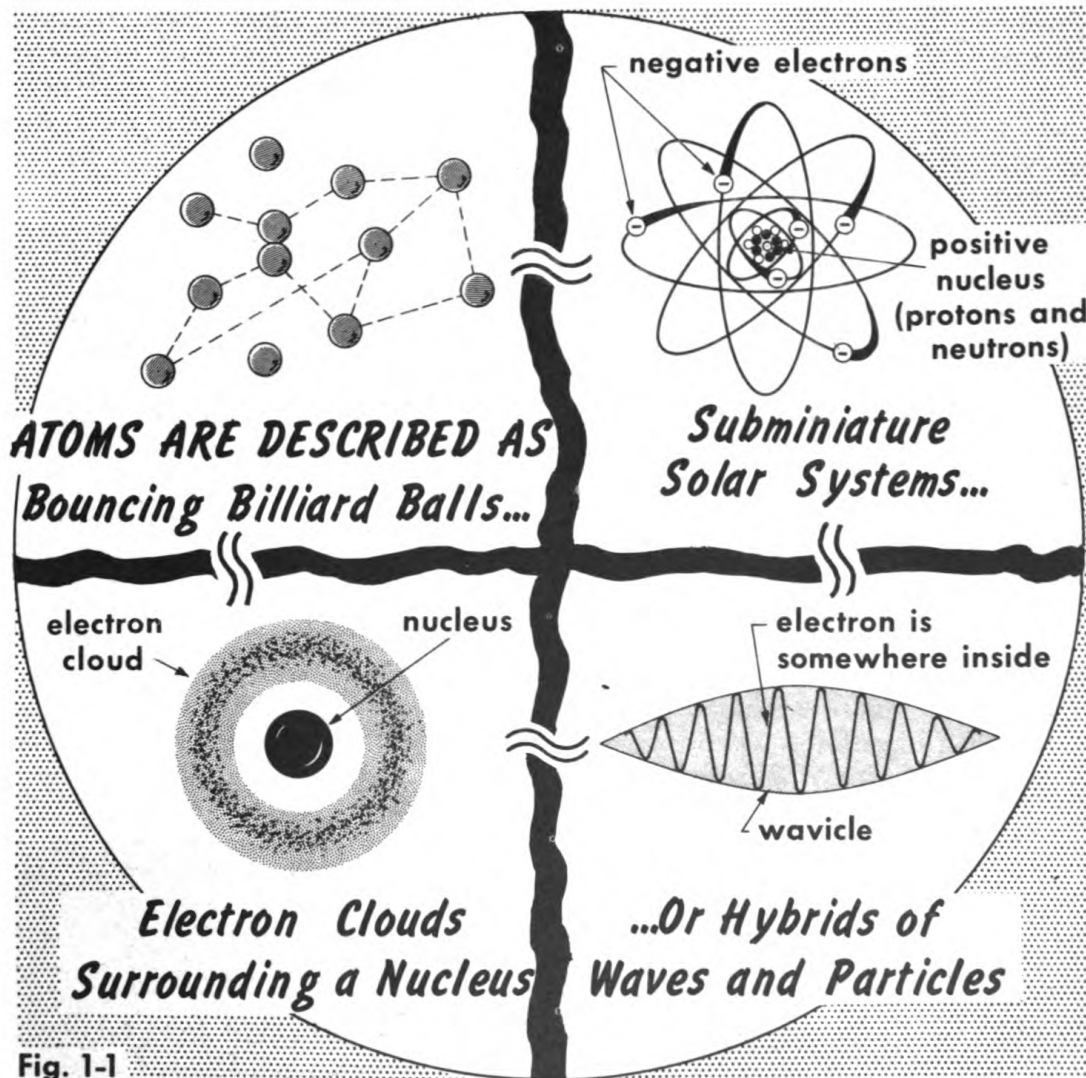


Fig. 1-1

bouncing billiard balls, submicroscopic solar systems consisting of planetary electrons and a stationary *nucleus*, fluffy clouds of electrons surrounding a charged nucleus, hybrids of mysterious waves and solid particles (*wavicles*), or what have you; but what are they, "really?"

If reality means to you what things are like apart from their environment and when no one is looking, you can—by definition—never know it. The

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physicist's reality is of quite a different sort. His reality is made up of experimental data, hypotheses, theories, equations, constructs and models—and it is everchanging. A set of equations that explains and predicts the phenomena he observes in the laboratory are all the reality a physicist asks for. If these equations can be interpreted pictorially through a construct or model, so much the better, but it isn't really necessary. Generally, as a mathematical theory becomes more refined and explains progressively greater experimental areas, its pictorial interpretations and models tend to fall by the wayside, until (frequently) nothing more remains than a few abstruse mathematical symbols. These symbols are, however, as real to a physicist as any picture you could draw; moreover, if the mathematical "picture" should change to accommodate new or contradictory experimental data, the physicist will happily accept these new and everchanging aspects of his reality.

Thus it has been with the atom. By its very nature the structure of the atom cannot be seen. The shortest wavelength of visible light (violet) is about a hundredthousandth of an inch, and the diameter of an atom is at least a thousand times smaller. Although a sort of supermicroscope using invisible rays of ions (charged particles) has revealed clusters of atoms, it does not let us peek inside. The invisible radiation interacts with the particles in the atom, thus knocking them about and making it impossible to observe the atom's structure. Consequently, all the evidence about the structure of the atom necessarily is circumstantial.

The circumstantial nature of the evidence about the atom accounts for the variety of atomic pictures and models. Different models fit different experimental data, and no single model fits all available data. Thus, looking at the forked tracks of one of the *alpha particles* (charged helium atoms) in the *cloud chamber* photograph below (Fig. 1-2), it is hard to escape the conclusion that a collision—akin to that of two billiard balls—must have taken place between the alpha particle and another atom. The photograph was

### CLOUD-CHAMBER PHOTO of ALPHA-PARTICLE TRACKS in AIR

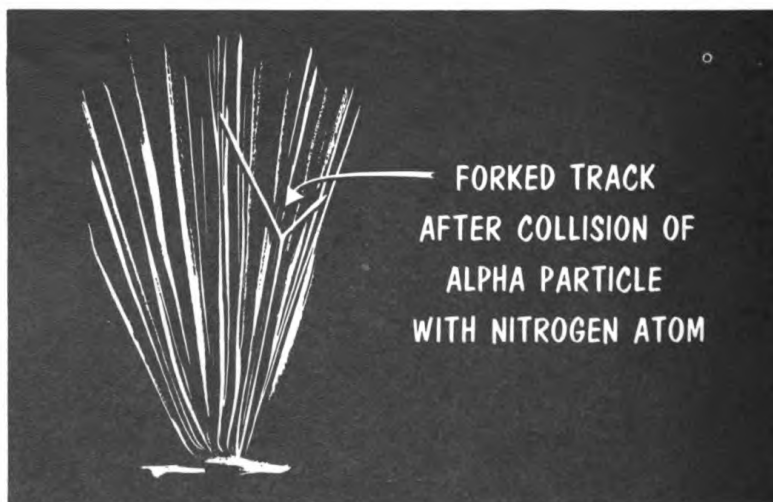
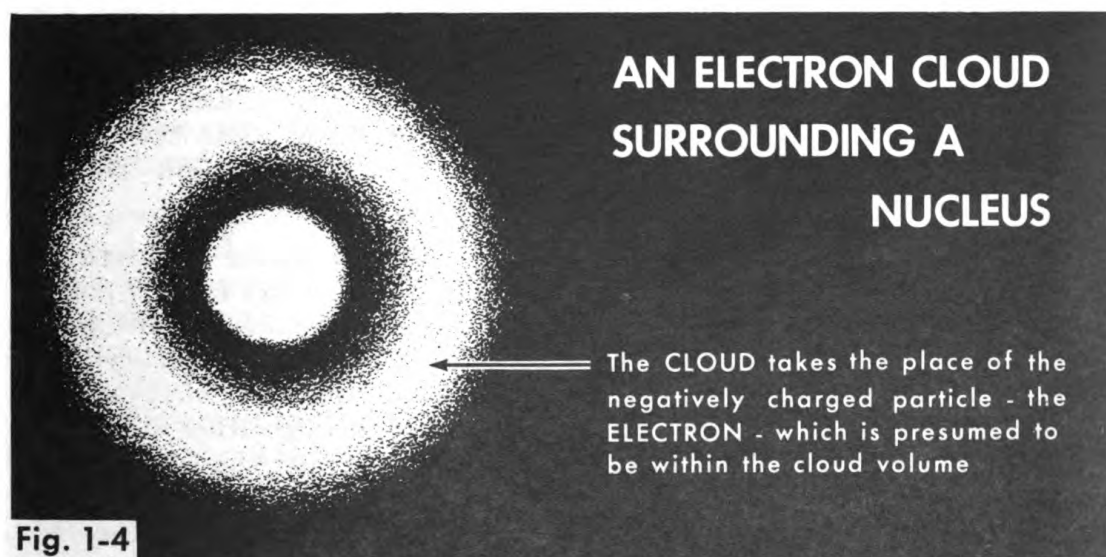
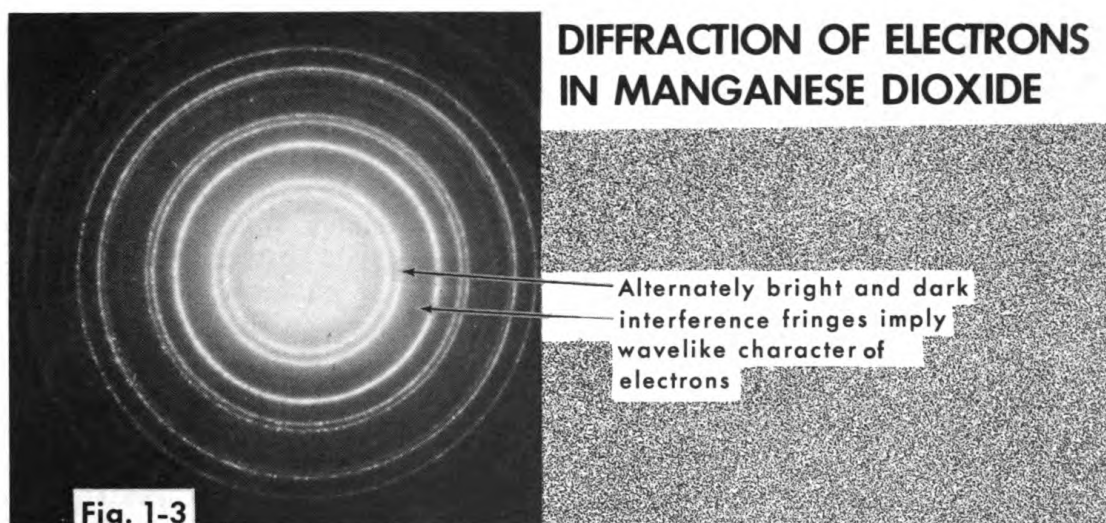


Fig. 1-2

## THE ATOM AND ITS NUCLEUS

made by suddenly expanding moist air in a *cloud chamber*, resulting in the condensation of little cloud droplets on the charged atoms. The tracks of the condensed water droplets show the paths of the individual alpha particles. The forked track at right shows the collision of an alpha particle with a nitrogen atom, which resulted in the capture of the particle and the emission of a proton.

A very different story is told by Fig. 1-3, which shows the result of electron *diffraction* in manganese dioxide. The alternately bright and dark fringes can be explained only by the familiar phenomenon of interference between waves, and so electrons must be assumed to be wave-like in character. Other evidence can be cited (Fig. 1-4) to prove that electrons are particles. These apparent contradictions have been resolved in a subtle mathematical theory, called *wave mechanics*, from which *both* the wave and parti-



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cle properties of the electron can be deduced. Regrettably, however, the theory does not lend itself to the construction of any model or picture familiar to our experience.

According to the principles of wave mechanics it is not possible to locate an electron at any particular spot within the atom, but only possible to specify the *probability* of locating it within a certain volume inside the atom. This has led to the picture of the atom as a positively charged nucleus surrounded by a negatively charged *electron cloud* of a given density. The electron is not actually a charged cloud, but since it is not possible to specify just where the electron is at any time, the effect is the same as if an electron cloud with a distributed charge were present.

### The Bohr Atom

Interesting as the theories we have briefly touched upon may be, let us now concentrate on the simple *planetary model* of the atom, suggested by the British scientist Lord Rutherford and developed (in 1913) by the Danish physicist Niels Bohr. This model explains so many features of atomic behavior that it is still highly useful today. The simplest kind of atom is the hydrogen atom. Bohr pictured the hydrogen atom as consisting of a single negative electron moving in a circular orbit about a tiny positive nucleus, composed of one proton (Fig. 1-5). The diameter of the smallest possible electron orbit is about *four billionths of an inch* ( $4 \times 10^{-9}$  in), but the positive nucleus is concentrated into a space that is only about 1/10,000 the diameter of the orbit. If the electron orbit was enlarged to the dimensions of the Empire State Building, the nucleus would be the size of a ping pong ball at its center, and a solitary, baseball-size electron would circle the ping pong ball at a distance of 500 feet. As another illustration, if the hydrogen nucleus were magnified to the size of the earth, the electron would be a large planet orbiting around the earth at a distance about halfway between the earth and the sun. Evidently, the atom is mostly empty space, and it appears that Democritus' void is very real indeed.

Though the electron is somewhat larger than the proton, the mass of the atom is concentrated in the nucleus. The proton weighs about 1840 times as much as an electron. Electrons are so light that 30,000 trillion trillion of them would weigh less than 1 ounce.

What keeps the electron circling in its orbit? As is true for the earth satellites or the sun and its planets, the outward (*centrifugal*) force due to the energy of motion must be exactly balanced by an opposing inward (*centripetal*) force. In contrast to planetary bodies, however, the necessary inward force in the atom is not furnished by gravitational attraction, but by the *electrostatic attraction* between two unlike charges—the positive nucleus and the negative electron. This would work fine, except that the laws of classical physics require an electron spinning in its orbit to give up energy by radiation. Because of this loss of energy the electron could be expected to spiral gradually into the nucleus, rather than remain in a stable orbit.

## THE ATOM AND ITS NUCLEUS

### THE HYDROGEN ATOM AS PICTURED BY BOHR

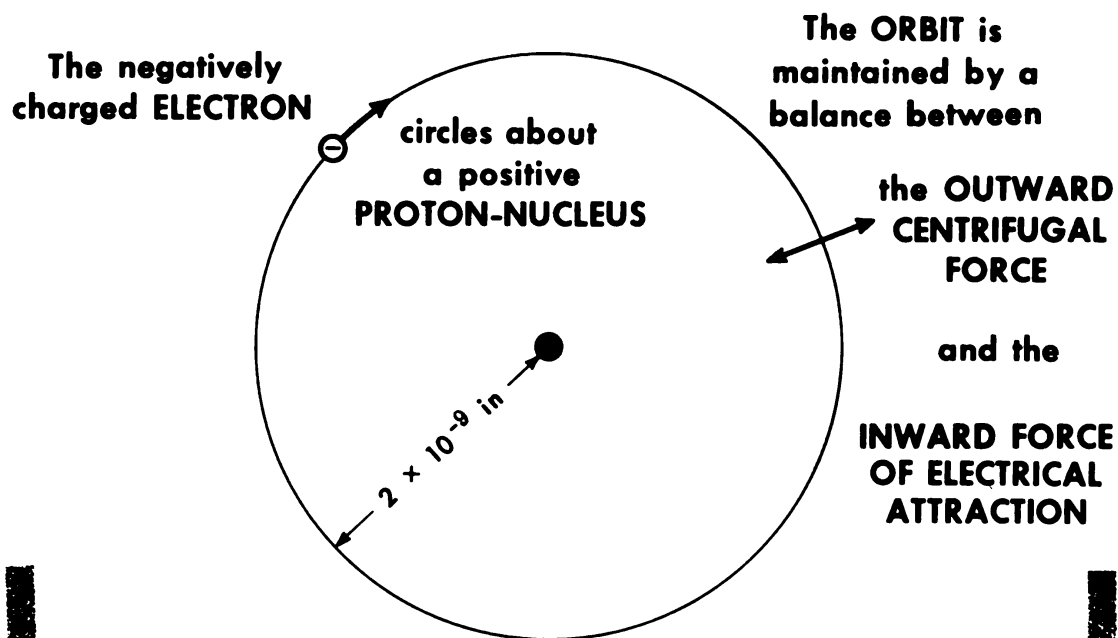
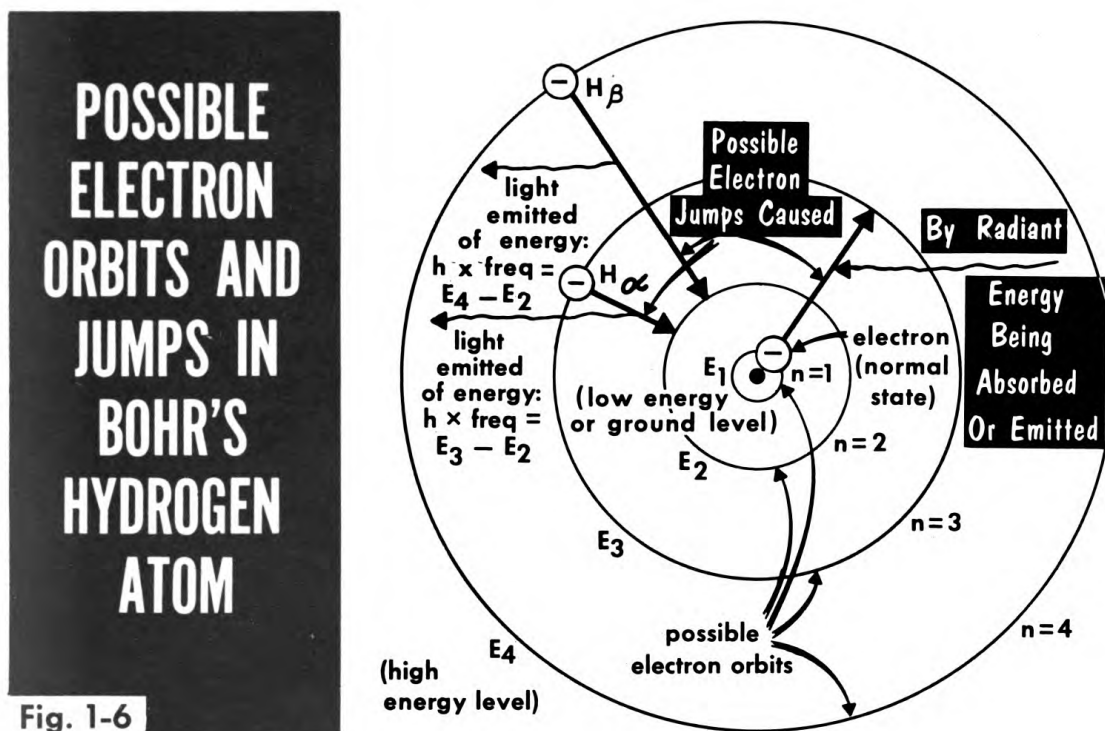


Fig. 1-5

Bohr, however, made the radical assumption that an electron does *not* radiate energy while spinning in a closed orbit. According to Bohr, the electron may rotate in a number of discrete orbits (Fig. 1-6), each associated with a definite amount of energy and a specific radius. These are known as the *stationary* (steady) states of the atom. The radius of the orbit and the energy ( $E$ ) associated with it can change only in unit jumps (quanta), defined by a *quantum number*,  $n$ . When  $n = 1$ , the electron is in the smallest possible orbit and has the lowest possible energy ( $E_1$ ). This is known as the *ground level* or *normal state*. When  $n = 2$ , the radius of the orbit is *four* times as large and the energy ( $E_2$ ) is correspondingly increased. When  $n = 3$ , the radius is *nine* times as great and the energy ( $E_3$ ) is further increased, and so on.

The particular orbit or energy level occupied by the electron at any time depends on the energy imparted to the electron. When the hydrogen atom *receives* energy, and is said to be *excited*, the revolving electron jumps from the ground state to a larger orbit, in opposition to the electrical attraction of the nucleus. How far it jumps—to one of the permissible orbits—depends on the amount of excitation energy. If sufficient energy is absorbed, the electron may be knocked beyond the outermost stationary orbit and be freed from the atom entirely. The atom is then said to be *ionized*, and since it has lost its electron, it is left with a net *positive* charge. (The atom is normally electrically neutral.)



Hydrogen atoms may be excited in a number of ways. One method is to introduce hydrogen gas at low pressure into an evacuated tube and discharge an electric current through the tube. This results in numerous collisions between the hydrogen atoms and the "free" electrons of the current, causing excitation or ionization of the hydrogen atoms. Excitation may also be produced by injecting hydrogen gas into a carbon arc, a hot flame, or an electric spark. Regardless of the method used, when hydrogen atoms are excited, the gas gives off a characteristic glow, whose color (frequency) components can be analyzed with a spectroscope. (A spectroscope is a more accurate version of the familiar toy prism that produces a rainbow color spectrum from ordinary sunlight.)

When the glow of excited hydrogen gas is analyzed, it is seen to consist of a few characteristic colors, each of a specific frequency or wavelength. (Wavelength is inversely related to frequency.) As shown in Fig. 1-7 the visible spectral lines occur in the red, blue and violet regions of the sun's spectrum, which is shown for comparison. The four major lines are labeled  $H\alpha$ ,  $H\beta$ ,  $H\gamma$ , and  $H\delta$ .

The remarkable success of Bohr's atomic model is primarily due to the fact that it accurately explains the emission of light and other radiation. When the electron of an excited hydrogen atom returns to its normal lowest energy level ( $n = 1$ ), either directly or in a series of orbit-to-orbit jumps, it gives up energy in the form of radiation. The frequency of the emitted radiation

## THE ATOM AND ITS NUCLEUS

### COMPARISON of the VISIBLE SPECTRUM of the SUN with that of HYDROGEN

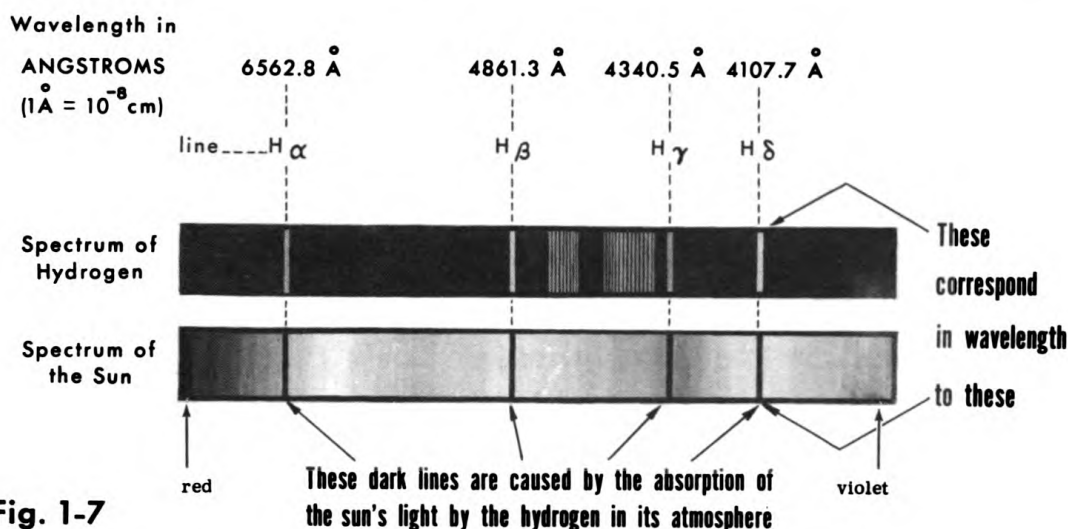


Fig. 1-7

(multiplied by a constant " $h$ "), known as *Planck's constant*, is exactly equal to the *difference in energy* between the orbits. It turns out that all the visible lines in the hydrogen spectrum are caused by electron jumps from a high energy orbit to the second innermost orbit ( $n = 2$ ). Thus the red H $\alpha$  line in the hydrogen spectrum is emitted, when the electron jumps from the third innermost ( $n = 3$ ) to the second innermost orbit ( $n = 2$ ); the blue H $\beta$  line is caused by a jump from the fourth ( $n = 4$ ) to the second orbit, and so on. (Refer back to Fig. 1-6.) Moreover, if the frequency of the emitted lines is computed from the difference in the energy levels of the Bohr orbits, the result checks exactly with the frequencies obtained from spectral analysis. This is not only true for the visible lines, but also for a series of lines in the ultraviolet region, caused by electron jumps to the innermost orbit ( $n = 1$ ), and a further series of lines in the infrared region, caused by electron jumps to the third innermost orbit ( $n = 3$ ). The spectrum analysis of hydrogen thus provides confirmation of Bohr's atomic theory.

Although the theory was brilliantly successful in explaining the observed behavior and spectrum of the hydrogen atom, it proved to be insufficient to account for some of the finer effects, such as the fact that the spectral lines were found to consist of groups of finer lines when observed with a spectroscope of high resolving power. To account for this and other phenomena, various *elliptical* instead of purely circular orbits were assumed and the concept of *electron spin* was introduced. Even with these added complexities, the mechanical model of the atom could not account completely for the behavior of hydrogen and was even less successful when applied to more

## NUCLEAR ENERGY AND POWER REACTORS

complex atoms. We shall see in the next section how some of the results of wave mechanics paved the way for a more adequate picture of the atomic structure and behavior of complex atoms.

### Building up Atoms

One hundred and one elements have been identified thus far including some artificially produced elements, each of which correspond to a distinct type of atom. The building blocks for all these atoms are *electrons*, *protons* and *neutrons*. The electrons have a negative charge, the protons an equal *positive* charge, and the neutrons have no charge. The atomic mass (weight) of the proton and neutron are approximately equal and are taken as 1 in assigning atomic mass numbers to the various atoms. The relative weight of the electron is only about 1/1840 as great. The electrons are presumed to move in various orbits around the positive nucleus, which is made up of protons and *neutrons*. Since the atom is electrically neutral (unless it is *ionized*), the number of negative electronic charges must equal the number of protons in the nucleus. The number of protons in the nucleus of an atom, or equivalently, the number of orbital electrons, is called the *atomic number Z*. Because this number specifies the total nuclear (or electron) charge it has long been used for identifying the place assigned to chemical elements in the *periodic table* used by the chemist. The sum of the protons and neutrons in the nucleus of an atom gives it atomic *mass number A*. The number of neutrons in the nucleus, *N*, is the difference between this mass number and the number of protons, or  $N = A - Z$ .

Figure 1-8 shows a simplified view of the sodium atom, symbolized  ${}_{11}\text{Na}^{23}$ . (The subscript 11 stands for the atomic number *Z*, the superscript 23 for the mass number *A*, and Na is the chemical symbol for sodium.) As evident from

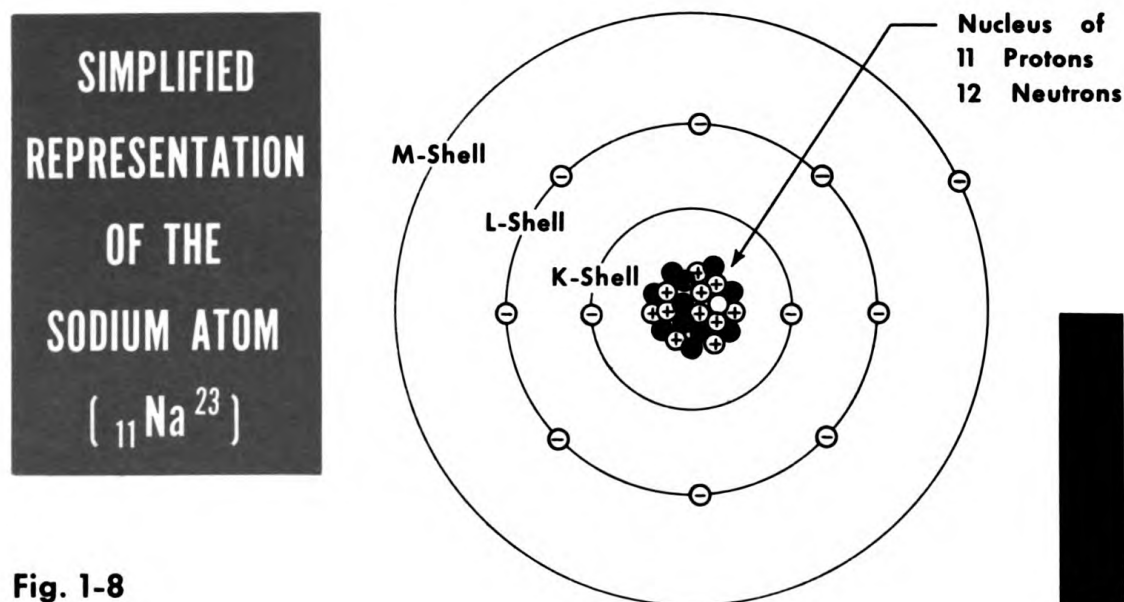


Fig. 1-8

## THE ATOM AND ITS NUCLEUS

the shorthand symbol, the sodium atom consists of 11 protons and  $(23 - 11)$  or 12 neutrons in the nucleus surrounded by 11 orbital electrons. The atom, thus, has the required total mass of 23 ( $A=23$ ) and is balanced electrically with 11 electrons outside the nucleus neutralizing the 11 protons ( $Z = 11$ ) in the nucleus. The 11 electrons are arranged in *shells*, two being in the first or *K shell*, eight in the second or *L shell*, and one in the third or *M shell*. (This terminology comes from X-ray notation.) The distances of these shells from the nucleus correspond to the Bohr orbits for hydrogen, the K-shell being equivalent to the ground level orbit ( $n = 1$ ), the L-shell to the second innermost Bohr orbit ( $n = 2$ ), the M-shell to the third innermost orbit ( $n = 3$ ) and so on. Shells removed still further from the nucleus, corresponding to quantum numbers of 4, 5, and 6, are known as the N, O, and P shells, respectively. As is to be expected, the electrons in the innermost or K shell are most strongly attracted to the nucleus, whereas the electrons in the more distant shells are progressively less strongly bound, and hence are more easily removed in chemical reactions. Although this two-dimensional representation of the sodium atom does not show it, no two of the electrons—even those in the same shell—have exactly the same orbit.

### Meet the Quantum Numbers

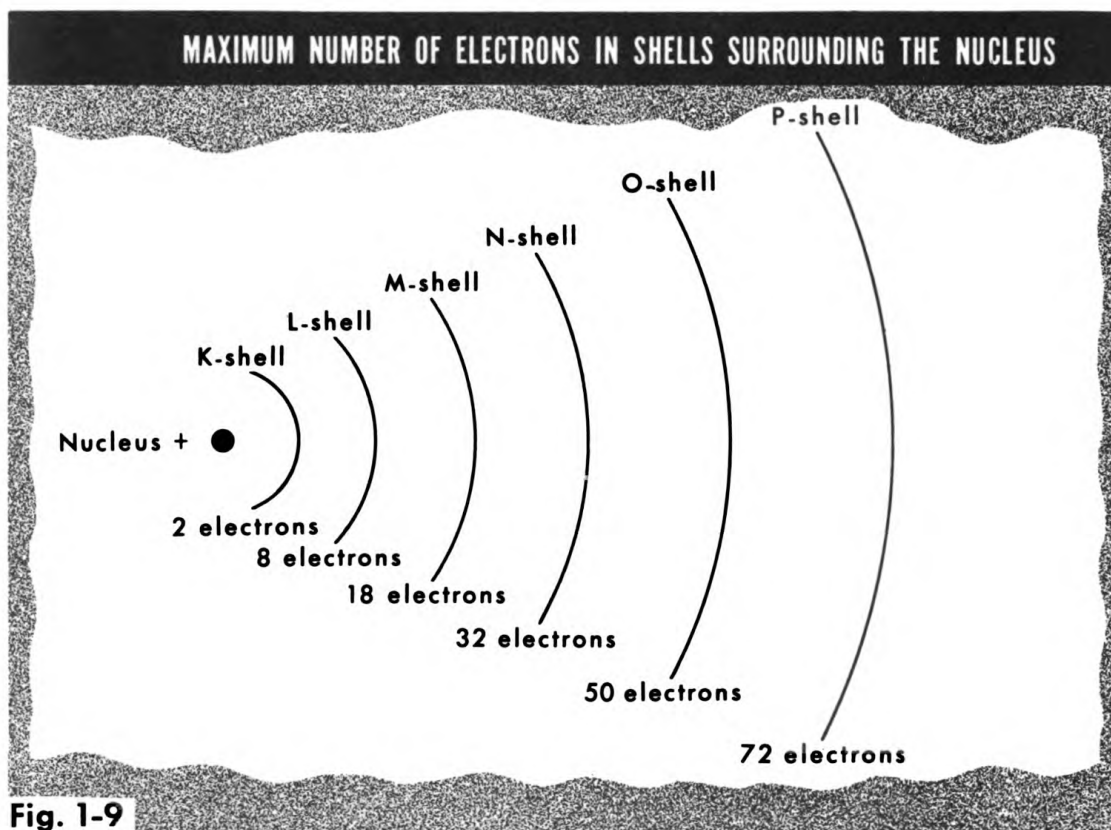
The arrangement of the 11 electrons in the sodium atom may appear to be rather arbitrary. Actually, it follows orderly rules, which specify that each electron shell can contain only a certain maximum number of electrons. Working from inside out, the K, L, M, N, O, and P shells may have a maximum of 2, 8, 18, 32, 54, and 72 electrons, respectively, as shown in Fig. 1-9.

The key to these “magic numbers” is a celebrated concept known as *Pauli's exclusion principle*. This states, in effect, *that no two electrons within an atom may have exactly the same orbit, or equivalently, can exist in the same state*. Now, the state or orbit of any particular electron can be completely specified by a group of *four quantum numbers*, usually called  $n$ ,  $l$ ,  $m_l$  and  $m_s$ . These quantum numbers originate from the esoteric depth of quantum (wave) mechanics and have no exact physical or pictorial interpretation. By referring them to our original Bohr atom, however, we can impose an interpretation that helps to visualize them.

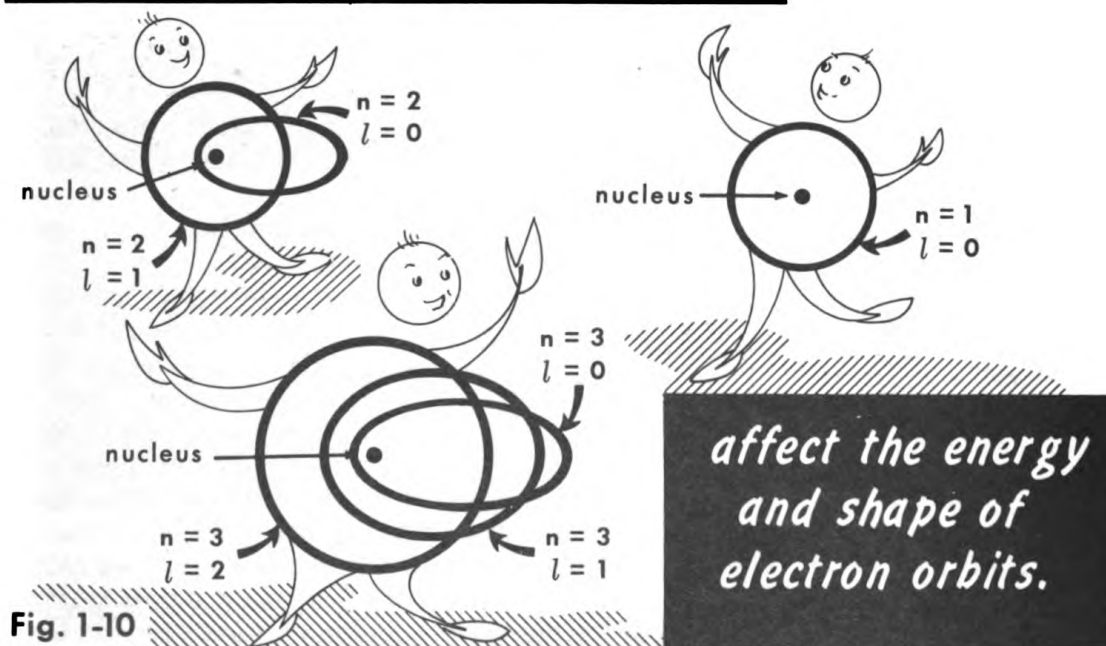
We have already met the principal quantum number,  $n$ , which determines the radius and energy level of the orbit. The value of  $n$  is always a positive, integral number (1, 2, 3 . . .). For a particular shell, the value of  $n$  is fixed (i.e., for the K-shell,  $n = 1$ ; for the L-shell  $n = 2$ , etc) and all the electrons in the shell have approximately the same amount of energy.

The second quantum number,  $l$ , frequently referred to as the *orbital angular momentum*, is connected primarily with the *shape* of the orbit in an equivalent Bohr atom. (See Fig. 1-10.) When  $l = 0$ , the electron orbit is an *ellipse* of maximum eccentricity (most flattened out). As  $l$  takes on larger positive values (1, 2, 3, . . . etc.), the ellipse becomes more and more rounded, and when

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## THE QUANTUM NUMBERS $n$ and $l$

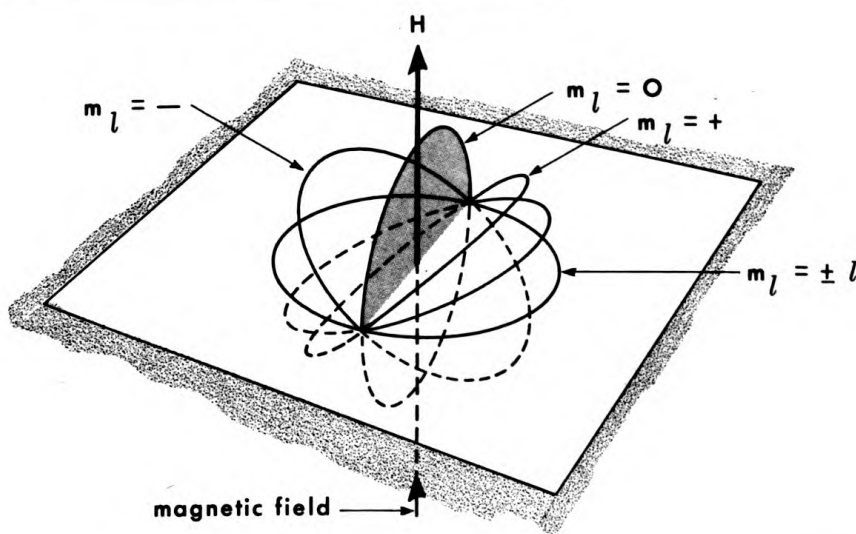


## THE ATOM AND ITS NUCLEUS

$l$  reaches its maximum value of  $n - 1$  (one less than  $n$ ), the orbit becomes circular. The value of  $l$  has a slight effect on the energy level of an electron, thus accounting for the "splitting" of the spectral lines of some elements.

The third or *magnetic quantum number*,  $m_l$ , determines the *orientation* of the plane of the electron orbit with respect to the direction of a strong magnetic field. (See Fig. 1-11.) Since an orbiting electron is a charge in motion, it

**THE MAGNETIC QUANTUM NUMBER  $m_l$**   
determines the inclination of the electron orbit with respect to a magnetic field ( $H$ )



It is maximum ( $\pm l$ ) when the orbit is perpendicular to the direction of the field, and zero when the orbit is parallel to the magnetic field

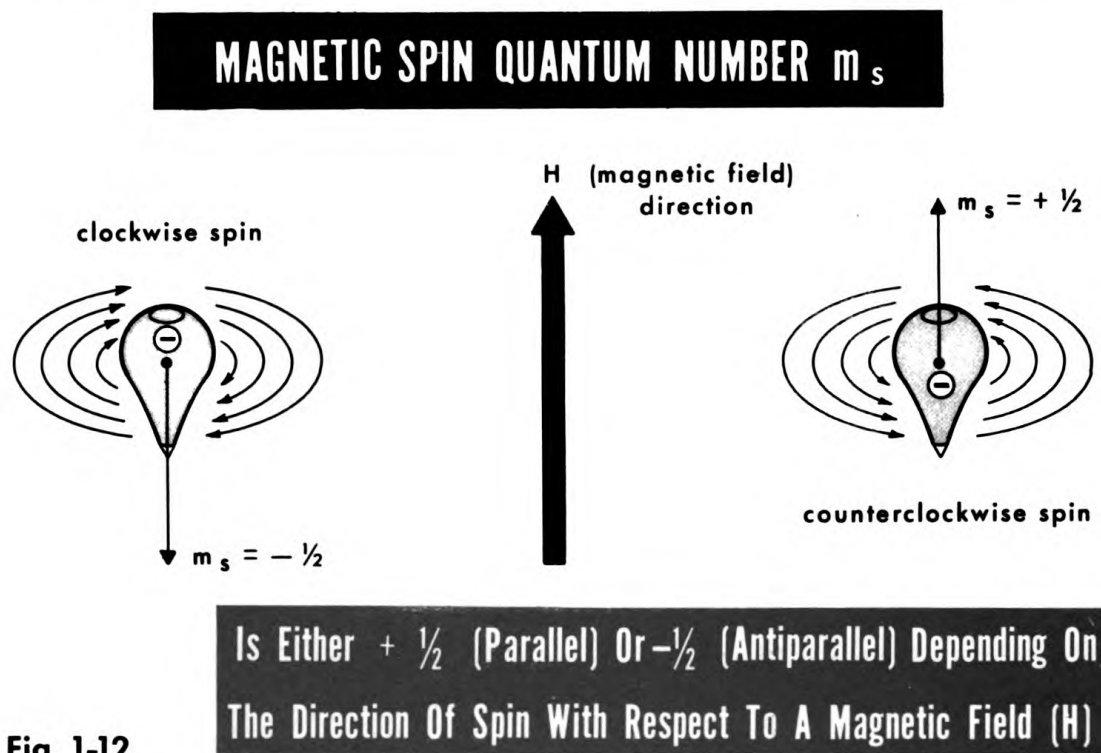
**Fig. 1-11**

represents a tiny electric current. Moreover, you may recall from basic electricity, that every current is surrounded by a magnetic field. If an electron is placed in a strong magnetic field, its own magnetic field and hence, the electron orbit, will tend to incline in certain directions with respect to the external field. These inclinations of the orbit are specified by the quantum number  $m_l$  which may have only integral positive or negative values from  $-l$  to  $+l$  ( $-1, \dots, -2, -1, 0, +1, +2, \dots, +l$ ); the maximum allowable values of  $m_l$  are  $+l$  and  $-l$ . When  $m_l = 0$ , the plane of the electron orbit is *parallel* to the external magnetic field, when  $m_l = +l$  or  $-l$ , the orbit is *perpendicular* to the field direction.

Finally, it is also assumed that an electron can spin on its axis like a top, either clockwise or counterclockwise. The fourth quantum number  $m_s$ ,

## NUCLEAR ENERGY AND POWER REACTORS

describes the direction of this spin. (See Fig. 1-12.) When it is spinning in this way, the electron behaves like a tiny magnet, and its spin axis aligns itself with the direction of any external magnetic field. Accordingly, the mag-



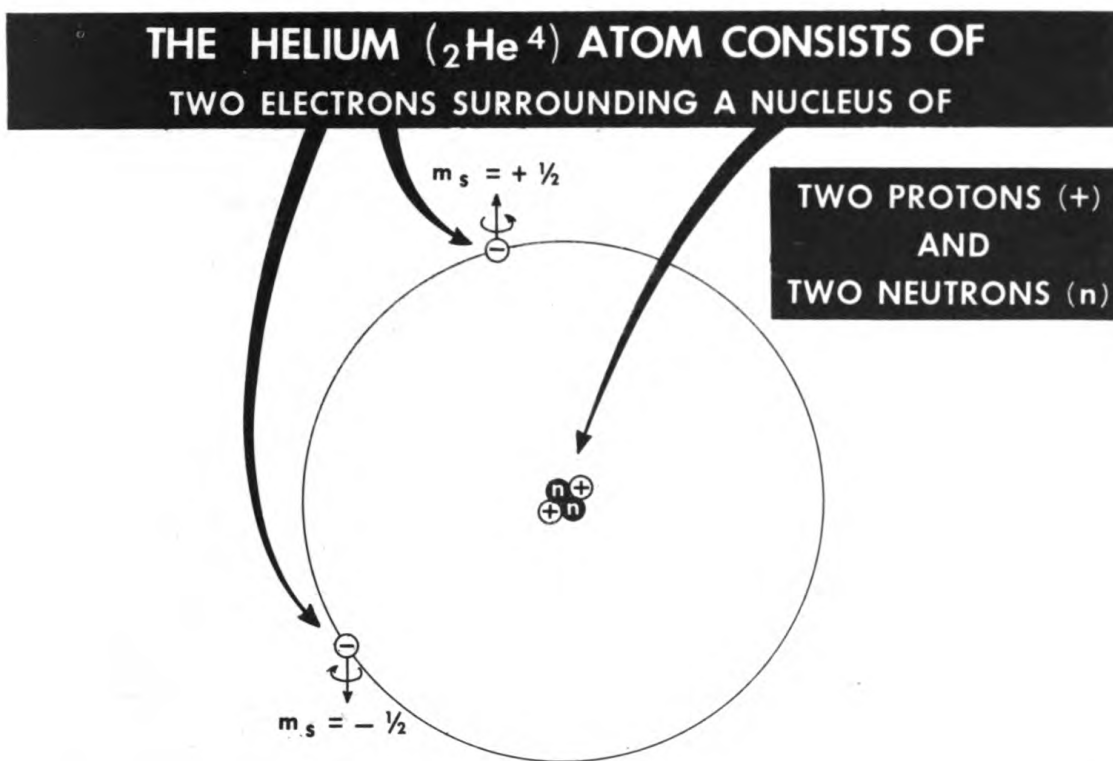
**Fig. 1-12**

netic spin quantum number  $m_s$  may have only *two* values, either  $+\frac{1}{2}$  for counterclockwise spin (the magnetic fields are parallel), or  $-\frac{1}{2}$  for clockwise spin (the magnetic fields are opposite or *antiparallel*).

### Using the Quantum Numbers

Remembering *Pauli's exclusion principle*—that no two electrons can have the same orbit or the *same set of quantum numbers*—we are now in a position to construct atoms in an orderly sequence. We have already met the atom of the simplest element, Hydrogen ( ${}^1\text{H}^1$ ), which consists of a proton in the nucleus and a single electron in the K-shell ( $n = 1$ ). Since the electron is in the lowest or ground energy level, where  $n = 1$ , quantum number  $l$  must be zero (one less than  $n$ ) and  $m_l$  is also zero. The electron spin,  $m_s$ , may be either  $+\frac{1}{2}$  or  $-\frac{1}{2}$ . The atom of the next element, Helium ( ${}^2\text{He}^4$ ), has both its electrons in the K-shell ( $n = 1$ ), one spinning clockwise ( $m_s = +\frac{1}{2}$ ) and the other spinning counter-clockwise ( $m_s = -\frac{1}{2}$ ) as shown in Fig. 1-13. Both quantum numbers  $l$  and  $m_l$  are zero. The nucleus of the helium atom contains two protons to balance the electron charge and two neutrons to make up an atomic mass of 4. The nucleus of the helium atom, which is particularly stable, is also known as an *alpha particle*. Since we have used up all available

## THE ATOM AND ITS NUCLEUS



**Fig. 1-13**

*It Is An Inert Gas Because Its Electron Shell Is Filled*

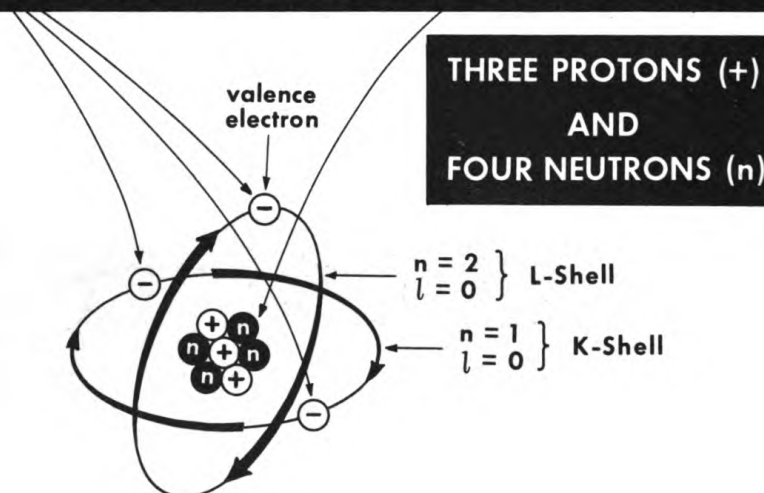
quantum numbers for the K-shell, no more than two electrons can be placed in this shell and it is now *filled* or closed. A closed shell makes for a very stable electron configuration. This is confirmed by the fact that helium is an *inert* gas that forms no chemical compounds. All the noble (inert) gases—helium, neon, argon, krypton, xenon, and radon—are characterized by filled outer electron shells.

Let us look at the third element in the periodic table, Lithium ( ${}^7_3\text{Li}$ ). The nucleus of this alkali metal consists of four neutrons and three protons. To balance the positive charge, three electrons must be placed in orbits around the nucleus. Two of these can be placed in the K-shell ( $n = 1$ ), but the third electron must be placed in a new shell, the L-shell ( $n = 2$ ), as shown in Fig. 1-14. This single electron may be detached easily, resulting in an *ionized atom*, or it may combine with another atom that lacks one electron in its outer shell, thus forming a *compound*. You will recall from elementary chemistry that lithium has a *valence* of  $+1$ , which makes it chemically very active. The reason for this is the extra electron in the outer or *valence* shell; thus, we may expect the other alkali metals, all of which have only one electron in their outer shell, to have a valence of  $+1$  and be very active (that is, form many chemical compounds). It is, for instance, true for sodium, which we discussed earlier, and for potassium, rubidium and cesium.

## NUCLEAR ENERGY AND POWER REACTORS

To ascertain the electron structure for the next few elements in the periodic table, we have to determine the maximum number of electrons that can be placed in the L-shell ( $n = 2$ ). Remembering that each electron must have a set of different quantum numbers, we proceed as follows: For  $n = 2$  and  $l = 0$ , the magnetic quantum number  $m_l$  must also be zero. The magnetic spin quantum number,  $m_s$ , however, may be either  $+\frac{1}{2}$  or  $-\frac{1}{2}$ . This permits two electrons in this  $l = 0$  orbit. Hence, we can place another electron, with opposite spin, in the  $n = 2, l = 0$  orbit of the Lithium atom, obtaining the electron structure of the Beryllium atom ( ${}^4\text{Be}^0$ ). Beryllium has four protons and five neutrons in its nucleus, thus balancing the electronic charge and making up a total atomic mass of 9.

### THE LITHIUM ( ${}_3\text{Li}^7$ ) ATOM CONSISTS OF THREE ELECTRONS SURROUNDING A NUCLEUS OF



**Fig. 1-14** *It Is A Very Active Element Because It Has Only One Electron In Its Outer Shell*

In addition to the  $n = 1, l = 0$  orbit, the L-shell may also have a circular Bohr orbit, for which  $n = 2$  and  $l = 1$ . In cases where  $l = 1$ , the magnetic quantum number  $m_l$  may be  $+1, 0$  and  $-1$  for variously inclined orbits. Moreover, the spin quantum number ( $m_s$ ) for each of these orbits may be either  $+\frac{1}{2}$  or  $-\frac{1}{2}$ , thus permitting two electrons to be placed in each of three orbits. This allows placement of *six* additional electrons in the  $l = 1$  orbits of the L-shell (that is, two for  $m_l = +1, m_s = \pm\frac{1}{2}$ ; two for  $m_l = 0, m_s = \pm\frac{1}{2}$ ; and two for  $m_l = -1, m_s = \pm\frac{1}{2}$ .) The L-shell, therefore, is filled with a total of *eight electrons*, two in the  $l = 0$  orbit and six in the  $l = 1$  orbits. This checks with the arbitrary rule stated earlier.

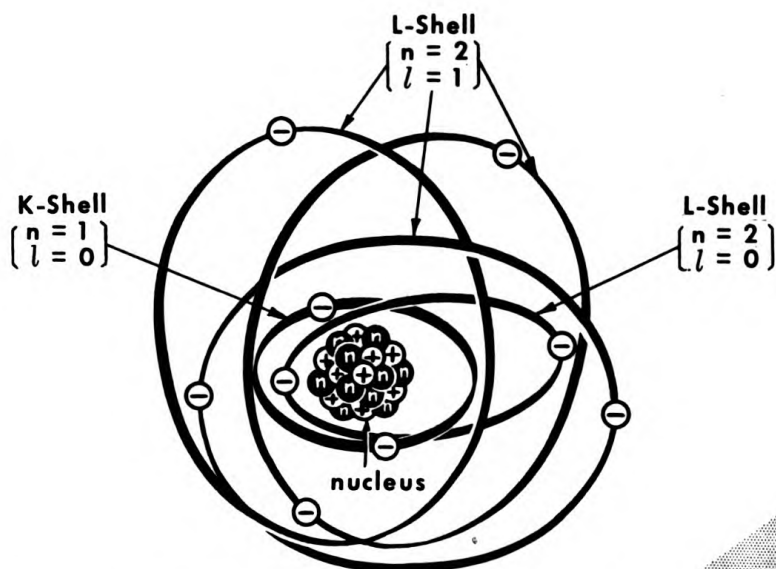
Filling the L-shell with the additional permitted electrons we obtain the entire second period of the chemical table of the elements, consisting (in

## THE ATOM AND ITS NUCLEUS

addition to Lithium and Beryllium) of Boron ( ${}^5\text{B}^{11}$ ), Carbon ( ${}^6\text{C}^{12}$ ), Nitrogen ( ${}^7\text{N}^{14}$ ), Oxygen, ( ${}^8\text{O}^{16}$ ), Fluorine ( ${}^9\text{F}^{19}$ ), and Neon ( ${}^{10}\text{Ne}^{20}$ ). The atom of fluorine (Fig. 1-15) is especially interesting, since it lacks only one electron to complete its outer shell. (In the chemist's language, its valence is  $-1$ .) The fluorine atom will do almost anything to capture this missing electron, and hence it forms compounds with virtually all the elements. In contrast, the neon atom, ( ${}^{10}\text{Ne}^{20}$ ) has a completed L-shell and is satisfied to remain a noble (inert) gas, forming no compounds with any element.

**THE FLUORINE ATOM  ${}^9\text{F}^{19}$  CONSISTS OF**

**NINE ELECTRONS SURROUNDING A NUCLEUS OF NINE PROTONS AND TEN NEUTRONS**



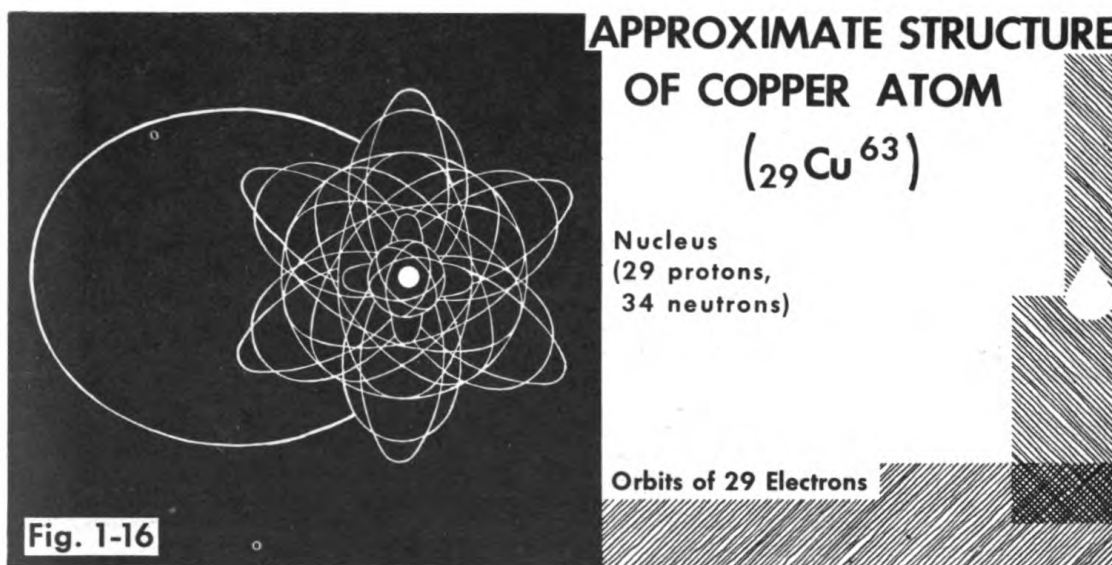
**Fig. 1-15**

We could go on building up the atoms of the periodic table of the elements, but as you can see from the illustrations of the copper atom shown in Fig. 1-16, this gets to be a pretty complicated process. Adding up the various combinations of the four quantum numbers, we can easily confirm that the M-shell can hold a maximum of 32 electrons, using the same reasoning that we employed for the L-shell. However, even the few examples we have given should suffice to reveal the harmoniously ordered structure of the atoms of all elements.

### "Atomic" Energy?

All the energy we use on earth derives from the atom, be it chemical, electrical or nuclear energy. When we drive an electric current through the

## NUCLEAR ENERGY AND POWER REACTORS



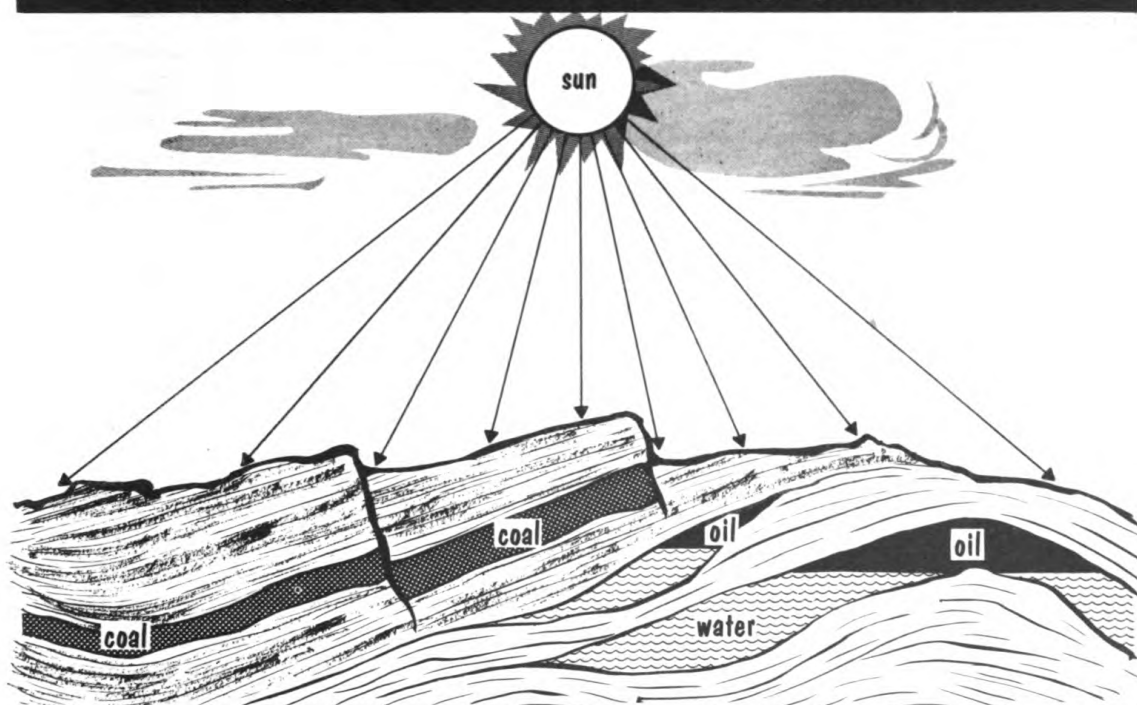
filament of a lamp or let it operate an electric motor, we make use of the work performed by free electrons, wandering from atom to atom within a conductor. Similarly, when we burn a substance or perform some other chemical reaction, we rearrange the atoms of the original substance to form new molecules and chemical compounds, obtaining considerable energy in the process. This rearrangement of atoms, however, involves only the electron structure (specifically, the electrons in the outer or valence shell) and leaves the nuclei of the atoms entirely unchanged. The chemical or electrical energy obtained in this way is meager compared to the tremendous energies liberated when we tap the forces that hold the nucleus of the atom together. We shall explore the origin of *nuclear energy* in the next chapter.

## 2: NUCLEAR FISSION AND THE CHAIN REACTION

### The Nucleus

The nucleus is the inner sanctum of the atom. It remains unchanged and untouched throughout all the physical and chemical transformations of atoms, that have supplied mankind with energy until our time. Yet, paradoxically, all our energy is derived from the sun, which itself is strictly a nuclear power plant. The sun irradiates the earth each day with an incredible amount of energy (Fig. 2-1). While we are able to extract this indirect solar

The daily quota of solar radiation falling upon the earth



equals the total amount of energy stored in coal, oil, and water since the beginning of earth

Fig. 2-1

energy, stored quite inefficiently in fossilized plant fuels, we have not yet been successful in making large-scale direct use of the sun's astounding energy supply. This, too, will be accomplished some day, but in the meantime we may rest content with the Promethean feat of having brought the sun's nuclear fire down to earth. Though as yet untamed, in the form of the hydrogen fusion bomb, in time we shall surely learn to control the fusion reaction, which is most akin to the sun's own nuclear transformations and promises literally unlimited amounts of power.

## NUCLEAR ENERGY AND POWER REACTORS

In this chapter we shall be concerned primarily with another nuclear reaction, that of *uranium fission* which exploded upon the consciousness of mankind in the last days of World War II. To understand the fission or breaking up of an uranium nucleus, we must first learn something about the forces that hold the nucleus of an atom together.

### Nuclear Forces

What holds the nucleus together? It cannot be *electrical* attraction, since neutrons have no charge and the protons—having like positive charges—*repel* rather than attract each other. It cannot be *gravitation*, since the gravitational attraction between the tiny nuclear particles (called *nucleons*) is far too slight to account for the actual forces and energies encountered. Yet a powerful attractive force must exist, or the nuclei of all atoms would fly apart because of electrical repulsion. We have to postulate, therefore, the existence of an entirely new attractive force, operating only within the extremely small dimensions of the nucleus and, moreover, considerably stronger than the electrical repulsion between the protons.

In 1935, the Japanese physicist Yukawa made exactly that assumption in his trail-blazing “meson” theory. He postulated the existence of powerful, short-range nuclear forces and related them to a new kind of short-lived, nuclear particle, called *meson*. Mesons are presumed to be transitory elementary particles with masses intermediate between those of the electron and of the proton (*meson* is Greek for “intermediate.”) It is these mysterious particles that cement the nuclei together. Different types of mesons have been detected since then and some have actually been created in powerful particle accelerators.

The short-range nuclear force binds all nuclear particles (nucleons) equally to each other, like droplets in a drop of liquid, regardless of whether they are protons or neutrons. The lighter nuclei (elements of low mass number) are best balanced and most stable when the number of protons and neutrons in the nucleus is about the same. By reviewing the structure of the stable, light elements discussed in Chap. 1 you can confirm that this is actually so. The helium nucleus, or alpha particle, is particularly stable because of the exact balance of the two neutrons and two protons. The hydrogen nucleus consisting of a single proton has a tendency to combine or *fuse* with other protons and neutrons to form the more stable helium nucleus, giving off considerable energy in the process. This is the basis of the sun’s *hydrogen fusion reaction*, which takes place at tremendously high temperatures.

The nuclei of the heavier elements (above  $Z = 20$ ) require a greater number of neutrons than protons to attain relative stability. This is necessary to enable the attractive forces between all the nucleons to overcome the rapidly rising repulsive force between the protons. The neutron-proton ratio reaches about 3 : 2 for one type of the element uranium,  ${}^{235}\text{U}$ , with 143 neutrons and 92 protons. Despite this large neutron-proton ratio, the repulsion between the

## NUCLEAR FISSION AND THE CHAIN REACTION

protons in this type (*isotope*) of uranium is so strong that the nucleus becomes highly unstable when just one more particle of any kind is added to the nucleus from the outside. The  $U^{235}$  nucleus then breaks into two approximately equal parts, with the release of an immense amount of energy. This is the basis of the famous *uranium fission reaction*.

### Radioactivity

Another heavy element, *radium* ( ${}^{226}\text{Ra}$ ) was found to be *naturally radioactive* over 50 years ago by Marie and Pierre Curie. They discovered that the nucleus of the radium atom disintegrates *spontaneously*, giving off three different types of radiation in the process. Since the exact nature of these radiations was not known at the time, they were simply called *alpha rays*, *beta rays*, and *gamma rays*. The emanations may be sorted out by placing a bit of radium or other radioactive substance inside a groove cut into a lead block and applying a strong magnetic field perpendicularly to the line of radiation (Fig. 2-2). When applied in the direction shown in the illustration, the mag-

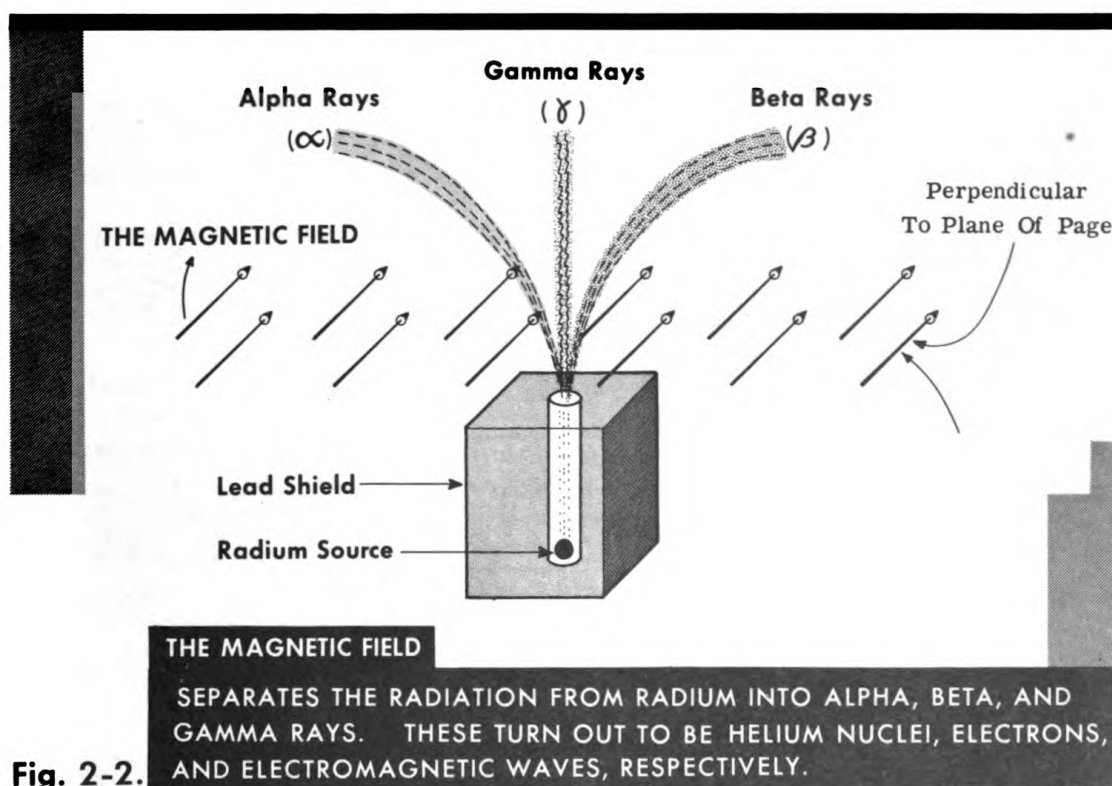


Fig. 2-2.

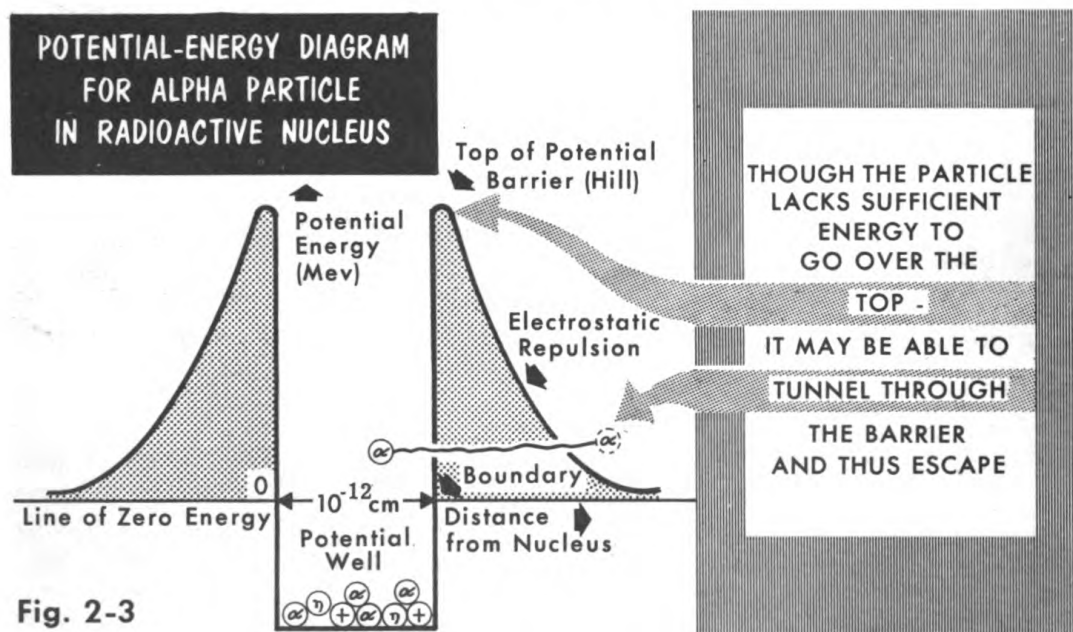
netic field has the effect of deflecting positively charged particles to the left, negatively charged particles to the right, but does not affect uncharged radiation. It then turns out that the alpha rays or particles are deflected to the *left*, the beta rays are deflected to the *right*, and the gamma rays are not deflected. Further investigation reveals that the alpha particles are positively

## NUCLEAR ENERGY AND POWER REACTORS

charged *helium nuclei* (ionized helium atoms), the beta rays are ordinary, negative *electrons*, while the gamma rays are electromagnetic waves, similar to X-rays, but shorter in wavelength.

The emission of alpha particles and electrons from the radium nucleus requires some explanation, especially since electrons are not presumed to exist inside the nucleus. We have mentioned that alpha particles are particularly stable and it is thus natural to assume that protons and neutrons inside the nucleus get together to form these stable units. The nuclei of radium and other heavy elements (uranium, thorium, etc.) may thus be visualized as a closely bound group of protons, neutrons and alpha particles, pushing each other around incessantly in the tight accommodations of less than a trillionth of an inch ( $10^{-12}$  cm). The alpha particle picks up energy by these continuous collisions with other particles, and eventually, after an astronomical number of collisions, it *may* manage to escape. Whether or not it actually does depends on the outcome of a tug-of-war of two forces—one is the short-range nuclear force of attraction that tends to keep the particle inside the nucleus, the other is the electrostatic repulsion between the alpha particle (charge =  $+2$ ) and the rest of the positive particles in the nucleus (protons and any other alpha particles).

The relation of the two forces acting upon the alpha particle can be visualized by means of a *potential-energy diagram* like that of Fig. 2-3. As long as the particle is inside the nucleus the nuclear force of attraction prevails;



once the particle is outside the nucleus, only the force of electrostatic repulsion acts, and the particle may simply "slide down the potential hill." Before it can do so, however, it must surmount the potential barrier, which is

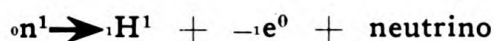
## NUCLEAR FISSION AND THE CHAIN REACTION

measured in millions of electron volts (1 electron volt is the energy an electron acquires when it is accelerated by an electric potential of 1 volt). Since the energy of the alpha particle inside the nucleus is normally close to the bottom of the "well", there is little or no chance that it ever will acquire sufficient energy to "go over the top."

The amazing thing is that when the energies of the alpha particles that *do* get out of the nucleus are measured, they are found to be millions of electron volts (Mev) *smaller* than the height of the potential barrier; by rights, *no particle should ever get out*, each being trapped forever within the potential well. Classical physics cannot explain this contradiction. By taking into account the *wave nature* of the alpha particle, however, wave mechanics demonstrates that there is a tiny but nevertheless real probability that once in a great while an alpha particle may simply "leak" or "tunnel through" the potential barrier. Moreover, the number of particles predicted to leak through in a certain time is in agreement with experimental results.

### What About Electrons in the Nucleus?

We still haven't resolved a second paradox—how electrons (beta rays) can be emitted from the nucleus when there are no electrons in the nucleus. This stumped physicists for quite a while, until they made the simple assumption that neutrons in the nucleus may *transform themselves into protons by throwing out an electron* (a beta particle). In the physicist's shorthand, this transformation is noted:



Note that the atomic number (subscript) and mass number (superscript) on both sides of the equation balance. Because the nucleus of a hydrogen atom is a proton, the symbol for a proton,  ${}_1^1\text{H}$ , is that of a hydrogen nucleus.

A BETA PARTICLE (ELECTRON) IS THROWN OUT OF THE  
NUCLEUS WHEN A NEUTRON TRANSFORMS ITSELF INTO A PROTON

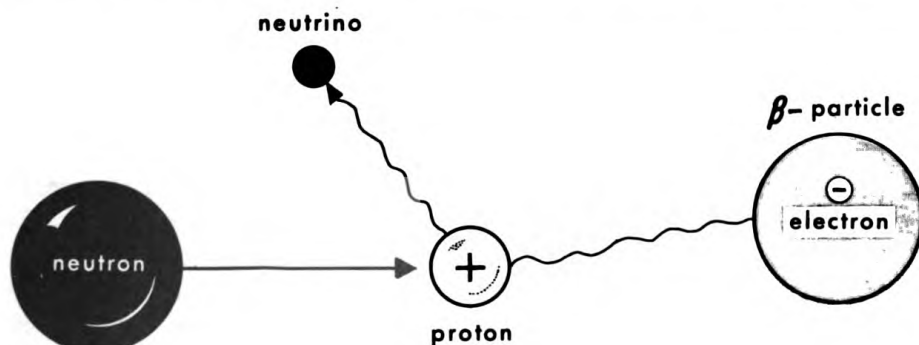
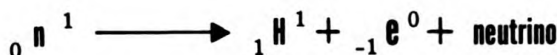


Fig. 2-4



## NUCLEAR ENERGY AND POWER REACTORS

Accompanying each beta particle emitted by the nucleus is another particle, called the *neutrino*, which carries most of the energy in the reaction, but has a small mass and no charge. (Because of this, it was not discovered until recently.)

### What are Gamma Rays?

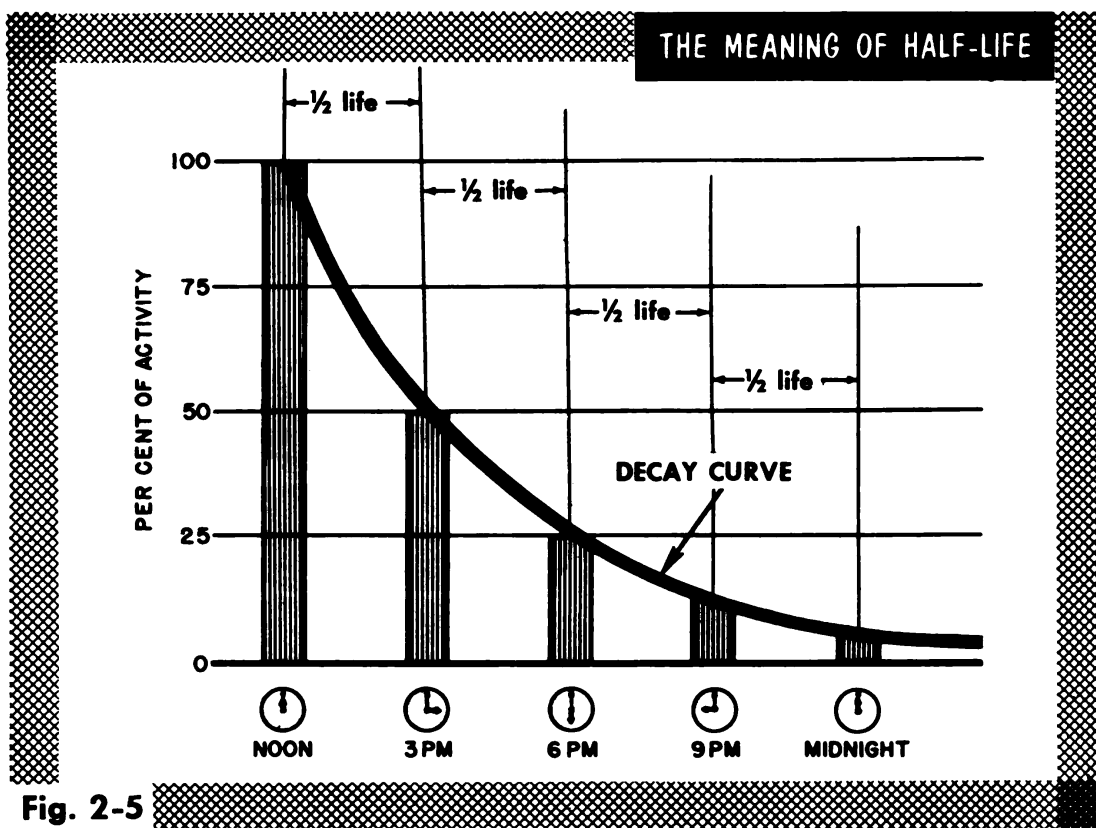
In the last chapter we saw that light and other electromagnetic radiations are emitted due to changes in the energy levels of electrons (electron jumps) in excited atoms. Similarly, *gamma rays* (X-rays of very short wavelengths) are emitted because of *energy changes within the nucleus*. When an alpha particle is emitted from a heavy nucleus, the nucleus is frequently left in an excited energy state. The nucleus then returns to its normal condition by releasing the excess energy in the form of electromagnetic radiation—gamma rays.

### How Many Half-Lives Make a Life?

Since the emission of alpha and beta particles from radium and other radioactive elements results in a loss of mass and a change in charge of the nucleus, it is evident that new elements are formed in the process. If these new elements are again radioactive, they will disintegrate into still other *daughter* elements. Radium, for example, is found to be a member of a radioactive *series* or family, whose original parent is ordinary uranium ( ${}^{238}\text{U}$ ). Uranium disintegrates—by alpha emission—into the daughter element *thorium* ( ${}^{234}\text{Th}$ ), which in turn transforms itself (by beta emission) into *protactinium* ( ${}^{234}\text{Pa}$ ), and so on. Some other members in the uranium series are radium, radon, polonium, bismuth, thallium, and lead. Lead is stable and, hence, the series ends with it.

From the way we rattled off the series, you might get the idea that uranium changes to lead almost at once. Actually, it takes *billions of years* for the whole series to complete itself, and the rate varies from element to element. The rate at which a radioactive element decays, known as its *activity*, is proportional to the total number of radioactive atoms present at any time. As more and more nuclei disintegrate and fewer are left, the decay rate decreases slowly in a *logarithmic* manner (Fig. 2-5). Under these conditions it would take an infinitely long time for all the atoms originally present to disintegrate. For this reason, the decay time or *period* is more conveniently specified by the *half-life* of the element. *The half-life of a radioactive element is the time required for half of the original nuclei to disintegrate*, so that only one-half (50%) of the original activity remains. If the half-life of a radioactive material is ten hours, for example, only one-half of the material will be present after ten hours and the original activity will have declined to 50% of its earlier value. After another half-life of ten hours, only one-half of the remaining material, or one-quarter of the original material survives, and the radioactivity will have declined to 25%. After another ten-hour half-life, only one-eighth of the original material remains, and activity is 12.5%.

## NUCLEAR FISSION AND THE CHAIN REACTION



The half-lives of the uranium series of elements we have mentioned vary widely, depending on the activity of each element. Thus, it has been found that it takes about 4.5 *billion* years for half of the relatively inactive uranium to disintegrate into thorium, while half of the thorium thus formed disintegrates into protactinium in only 24 days. Half of radium decays into radon in 1600 years, half of radon into polonium in about four days. The half-life of polonium is only about three *minutes*. The half-life of a radioactive element is, of course, a good indication how long the material will emit dangerous radiation.

### Nuclear Fission

The story of nuclear fission is a dramatic demonstration that great advances in technology are usually the byproduct of basic research. It begins in 1934, Enrico Fermi, then a professor of Physics in Italy, bombarded uranium with neutrons from a radium-beryllium source, in the search for elements of atomic number greater than 92. When he and his associates observed several beta-ray activities with half-lives other than those of the uranium series, they concluded that element 93 had been created. Other scientists soon joined in the international hunt for *transuranic* elements, particularly Irene Curie and Savitch in France, and Hahn, Strassman and Meitner in Germany. They bombarded various heavy elements with neutrons, observed many different

## NUCLEAR ENERGY AND POWER REACTORS

beta-ray activities, made careful chemical and physical tests, and generally ascribed the results to radioactivity in elements with atomic numbers 93 to 97.

It was not until 1939 when the "awful truth" dawned upon these scientists. In that year Hahn and Strassman discovered that one of the radioactive elements formed by the bombardment of uranium was of atomic number 56, the element *barium*. They suspected that uranium under the influence of the neutron bombardment was *breaking up into two nuclei* of lower atomic masses, rather than forming transuranic elements. If one of the nuclear fragments was barium ( $Z = 56$ ), the other had to be *krypton* ( $Z = 36$ ) to make up the atomic number of uranium ( $Z = 92$ ). The German scientists Meitner and Frisch soon showed that nuclear *fission* of uranium into two elements of lower atomic number was actually taking place and that the observed beta-ray activity was caused by the *fission fragments*. Moreover, calculations showed that the fission of uranium nuclei was accompanied by the release of large amounts of energy, in the order of about 200 million electron volts (200 Mev) per fission.

Word of the new process was brought to the United States by the Danish physicist Niels Bohr, and the experiments were quickly repeated and confirmed by Dunning, Nier, and other American scientists. They further observed that the fission of each uranium nucleus resulted in the emission of two or three free neutrons, which might cause additional fissions. With the realization that a self-sustaining *chain reaction* was theoretically possible and would result in the release of fantastic power, the stage was set for a new era of mankind. The feverish wartime race that resulted in the construction of the first self-sustaining nuclear reactor in Chicago in 1942, and the explosion of the atom bomb in 1945, is a part of history.

### The Mechanics of Fission

Fission is very much like the splitting of a drop of water by pricking it. We have mentioned that the particles in the nucleus of the atom stick together as the droplets (or molecules) in a drop of liquid. The attraction of the particles, both in the nucleus and in a drop of water, results in a spherical shape that resists deformation. However, if insufficient energy is supplied, both the drop of water and the nucleus split into two parts.

As shown in Fig. 2-6A the undisturbed uranium nucleus is spherical in shape and has an even distribution of positive charge (protons). The forces of repulsion due to this positive charge are in a delicate balance with the short-range nuclear forces of attraction.

In (B) a small amount of energy has been added by a neutron that has penetrated the uranium nucleus. This excess energy excites the nucleus; it starts to oscillate and becomes slightly deformed. As a result, the protons distribute themselves unevenly and their mutual repulsion leads to a concentration of charge at the ends. This usually causes still more violent oscillations and

## NUCLEAR FISSION AND THE CHAIN REACTION

When A Neutron Penetrates A Uranium Nucleus  
It Causes Deformation That Results In Fission

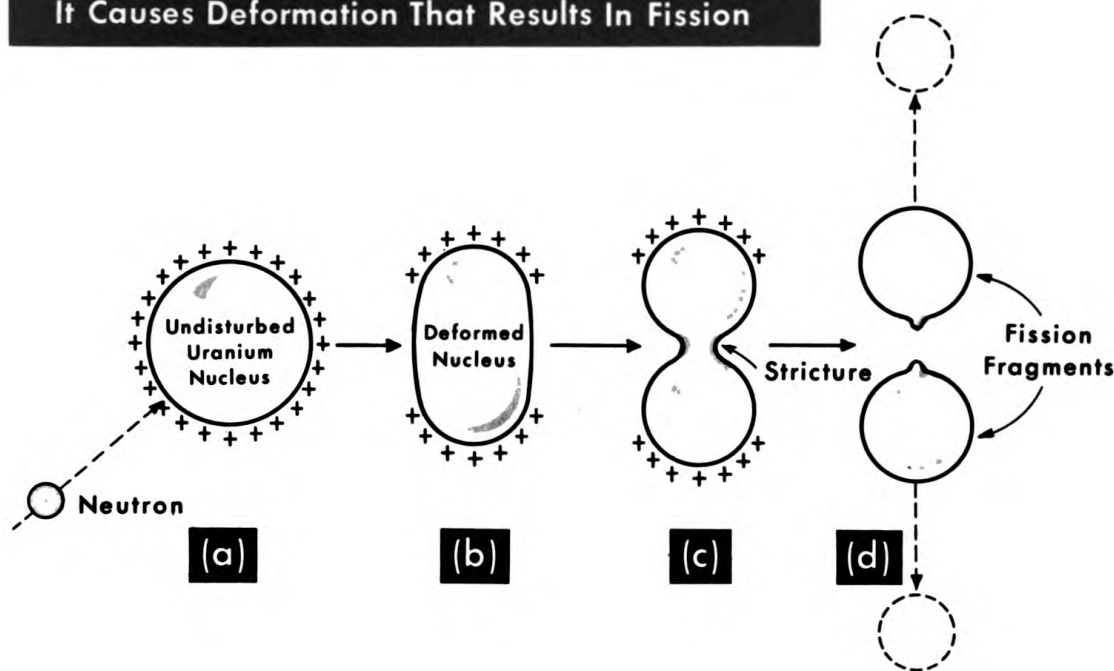


Fig. 2-6

### LIQUID-DROP MODEL OF FISSION PROCESS

the formation of a constriction between the halves, as in (C). Once a stricture is formed, the repulsive forces win out over the short-range attraction, and the nucleus tears itself into two parts (D). The fission fragments then are violently repelled in opposite directions, at high velocity and with resulting high *kinetic energy*. The whole process takes less than a *trillionth* of a second ( $10^{-12}$  sec).

#### Isotopes and Their Separation

Accurate observations have shown that uranium fission, when the element is bombarded with slowly moving neutrons, is *not* carried on by the ordinary variety with 146 neutrons ( ${}_{92}\text{U}^{238}$ ), but by a much rarer type, or *isotope*, of uranium with only 143 neutrons ( ${}_{92}\text{U}^{235}$ ). *Isotopes* are elements whose atoms have slightly *different masses* though all carry the *same charge* and hence are *chemically identical*. In other words, the nuclei of isotopes have the *same number of protons* (atomic number  $Z$ ) but *different number of neutrons* giving a different mass number (A).

Although we have assumed that the atomic mass of the elements is always a whole number (the sum of protons and neutrons), the experimentally determined masses of most elements are actually a *fraction*. This does not mean

## NUCLEAR ENERGY AND POWER REACTORS

that there are fractions of protons or neutrons in the nucleus, but rather that most elements are mixtures of isotopes and that the *weighted average* of the various isotopes turns out to be a fraction. For example, the element *lithium* occurs in nature in two isotopic forms, most of it (92.5%) being the run-of-the-mill variety  ${}^6\text{Li}$ , and a small proportion (7.5%) occurring as the isotope  ${}^7\text{Li}$ . Since they have the same atomic number ( $Z$ ), they are chemically inseparable, but the weighted average of the slightly different isotopic masses turns out to be 6.94.

Similarly, hydrogen has an atomic mass of 1.008 rather than 1.000, indicating the presence of isotopes. As shown in Fig. 2-7, there are three isotopes of hydrogen. One is the ordinary variety with 1 electron and 1 proton ( ${}^1\text{H}$ ), which makes up 99.98% of all hydrogen; the second—with 1 proton and 1 neutron—is “heavy” hydrogen or *deuterium* ( ${}^2\text{H}$ ), which occurs to the extent of about 1 part in 5000 (0.02%); finally, there is a man-made isotope of hydrogen, *tritium*, with 1 proton and 2 neutrons in the nucleus ( ${}^3\text{H}$ ). Both heavy isotopes are important in nuclear engineering. Deuterium ( ${}^2\text{H}$ ) is part of heavy water used as “moderator” and coolant in some nuclear reactors, while tritium ( ${}^3\text{H}$ ) is presumed to play an important role in the hydrogen bomb.

### HYDROGEN HAS THREE ISOTOPES

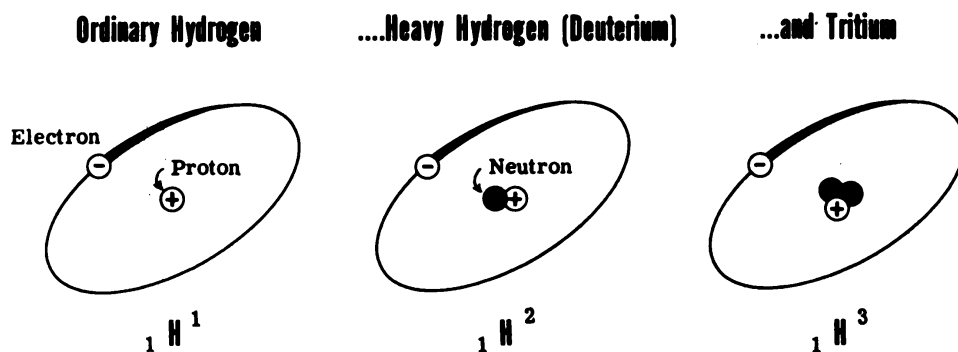
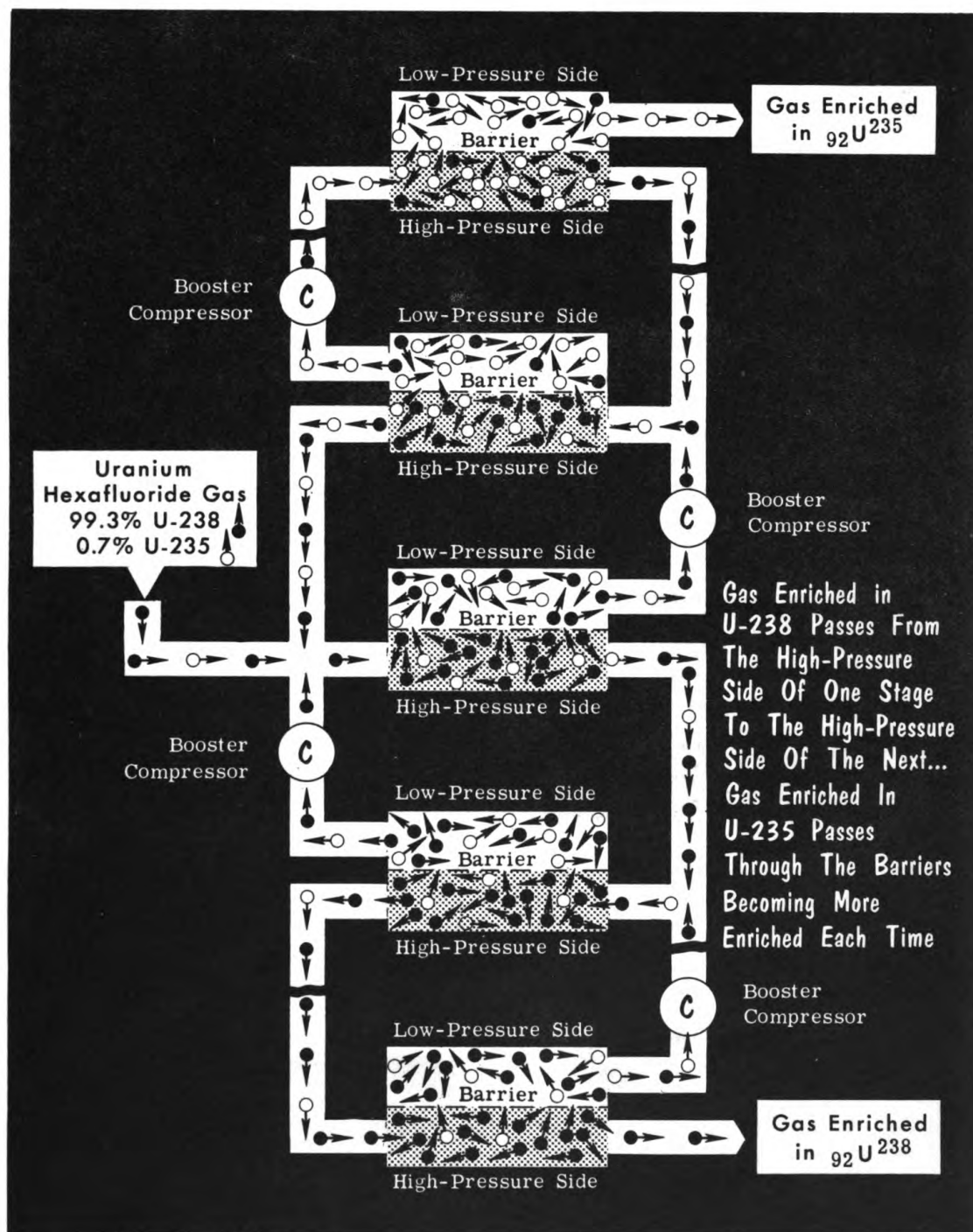


Fig. 2-7.

Since isotopes are chemically identical, their separation is an extremely difficult process. One successful method, known as *gaseous diffusion*, is based on the *slightly different rates* with which gaseous forms of isotopes travel through porous membranes. The isotope of uranium,  ${}^{235}\text{U}$ , that is important in fission caused by slow-moving (*thermal*) neutrons, occurs in natural uranium only to the extent of 1 part in 140 (0.71%). To separate U-235 from the abundant U-238, which cannot sustain a chain reaction, uranium hexafluoride gas containing both isotopes, is allowed to diffuse through thousands of consecutive (cascaded) stages of porous barriers at a mile-long

## NUCLEAR FISSION AND THE CHAIN REACTION



**ISOTOPES U-238 and U-235 ARE SEPARATED  
BY GASEOUS DIFFUSION, WHICH REQUIRES THOUSANDS  
OF IDENTICAL POROUS BARRIER STAGES**

Fig. 2-8

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gaseous diffusion plant in Oak Ridge, Tennessee, and similar plants at Paducah, Kentucky, and Portsmouth, Ohio. (See Fig. 2-8). One stream of gas becomes slowly *enriched* in the lighter U-235 component until a sufficient degree of purity is achieved for atom bomb production and nuclear reactor fuels. (A second stream of gas is correspondingly enriched in the heavier U-238.)

### U-235 Fission Reaction

The reason for going to the tremendous trouble of separating the U-238 from U-235 is that only the latter ( ${}_{92}\text{U}^{235}$ ) is fissionable by slow-moving neutrons, a process easily controlled in a nuclear reactor. U-235 is also fissionable by *fast* neutrons, a characteristic that is used in the uncontrollably violent chain reaction of the atom bomb. The more abundant isotope of uranium U-238 is occasionally also fissionable by *fast moving* neutrons (of more than 1 Mev energy), but more often than not it simply captures the colliding neutron and disintegrates radioactively into a new element, as we shall see later.

For industrial purposes, the most important fission reaction at the present is that of U-235, when bombarded with slowly moving neutrons (Fig. 2-9). The reaction that takes place may be written:

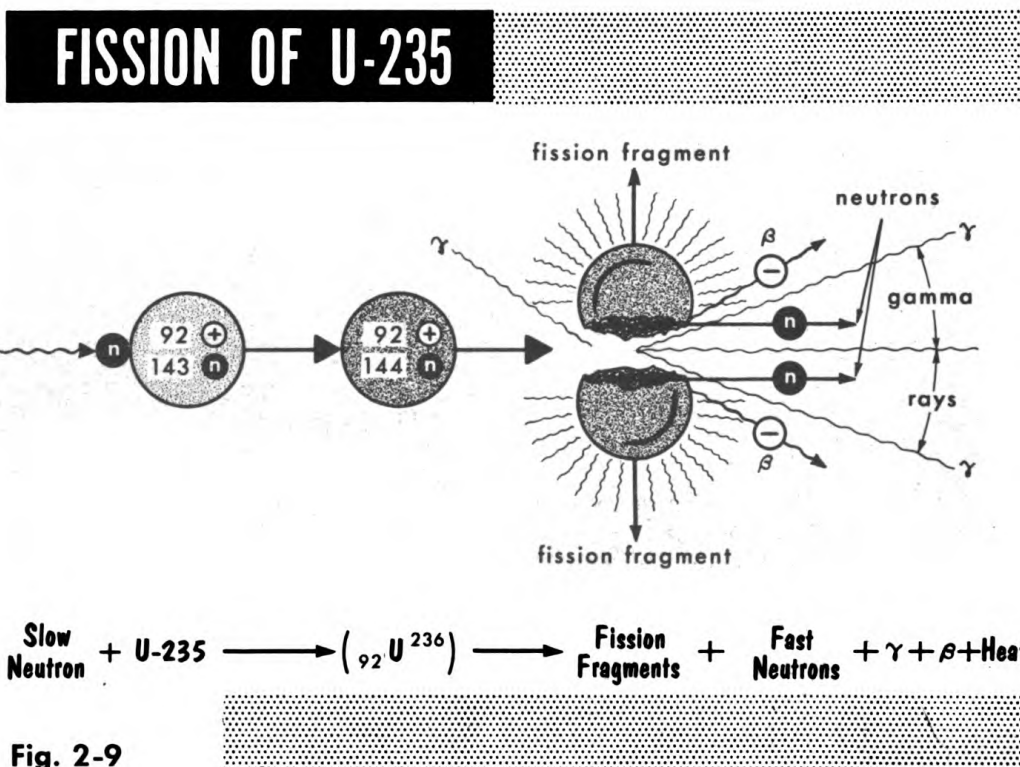


Fig. 2-9

## NUCLEAR FISSION AND THE CHAIN REACTION

In less technical terms this means that a slowly moving neutron is momentarily absorbed by U-235, forming the *compound nucleus*  ${}_{92}^{236}\text{U}$ , which immediately breaks into two fragments. The fission is also accompanied by the emission of 2.5 *fast* neutrons (on the average), beta particles, gamma rays, and neutrons, releasing a great deal of energy. The fractional number of neutrons is a weighted average, signifying that about half of the fissioned nuclei expel two neutrons, and the other half expel three neutrons.

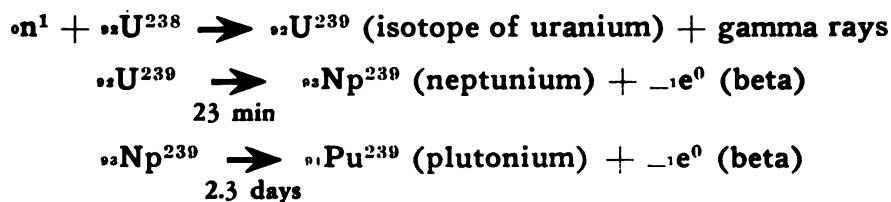
### Fission Fragments and their Products

Any number of combinations of fission fragments is possible, as long as the total mass of fragments and neutrons adds up to 236, the atomic mass of the U-236 compound nucleus. The fragments are *unequal*, one usually being a heavy element with a mass number around 140, the other being a light element with a mass of about 94. The fragments of a typical U-235 fission, for example, may be an isotope of strontium ( ${}_{38}^{94}\text{Sr}$ ), an isotope of xenon ( ${}_{54}^{140}\text{Xe}$ ) and two fast neutrons ( $2n^1$ ). You can verify that the atomic mass of these fission products adds up to 236 and their atomic number to 92, as required for the U-236 compound nucleus ( ${}_{92}^{236}\text{U}$ ). These isotopes of strontium and xenon, however, have far more neutrons in their nucleus than the heaviest known *stable* isotopes of the elements,  ${}_{38}^{88}\text{Sr}$  and  ${}_{54}^{136}\text{Xe}$ , respectively. They are, therefore, highly radioactive and disintegrate further through a whole chain of fission products, giving off gammas, betas (electrons) and neutrons in the process. The small fraction of neutrons that are emitted during radioactive decay, several seconds after fission, are known as *delayed neutrons*. Most of the neutrons (about 99%), however, are expelled within a trillionth of a second ( $10^{-12}$  sec) upon fission, and are called *prompt neutrons*.

The process of radioactive decay stops when stable isotopes have been formed, the end products in our example being zirconium ( ${}_{40}^{94}\text{Zr}$ ) and cerium ( ${}_{58}^{140}\text{Ce}$ ). Since there are many other possible combinations of fission fragments and radioactive decay chains, you can imagine that the total number of products due to multiple fissions is immense, possibly exceeding 250 isotopes.

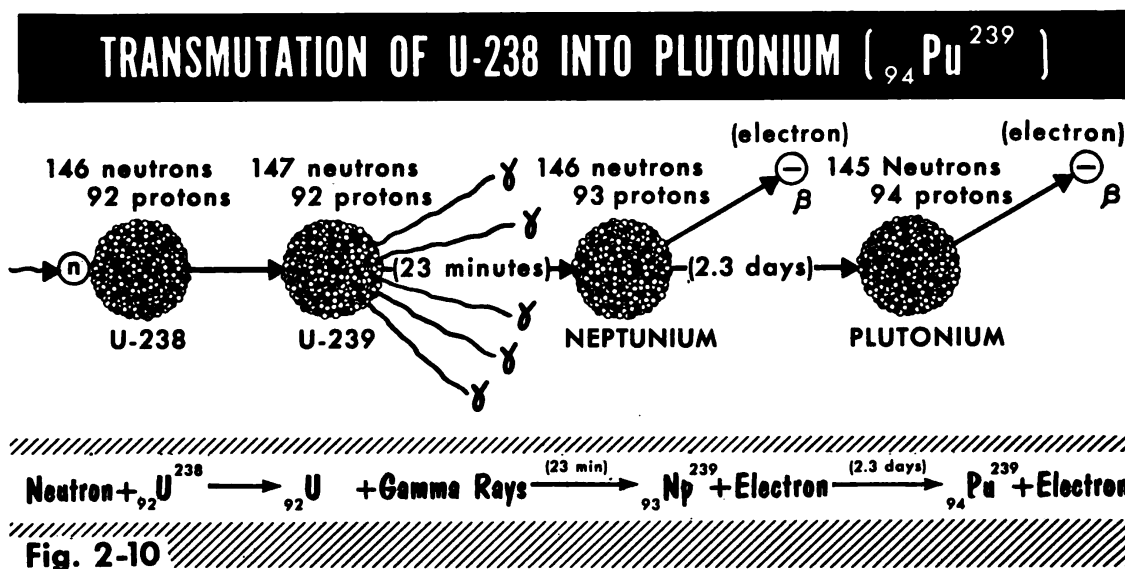
### Fission Fuels

We have mentioned that U-238 can be fissioned by bombardment with *fast neutrons*, but that it *captures slow neutrons* and transforms itself into two new *transuranic* elements—delayed payoff to the frantic search for transuranic elements back in 1934. The two new elements formed are *neptunium* ( ${}_{93}^{239}\text{Np}$ ), and *plutonium* ( ${}_{94}^{239}\text{Pu}$ ), elements 93 and 94 respectively. The set of reactions involved in the process may be written



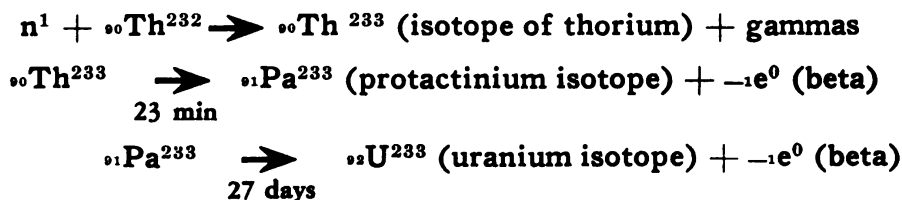
## NUCLEAR ENERGY AND POWER REACTORS

What happens in the above reactions is this: A slow neutron is captured by the U-238 nucleus, forming the compound nucleus  ${}_{92}\text{U}^{239}$ . (A new element is involved, since the positive charge,  $Z$ , has been increased by 1 through the emission of the electron, although the atomic mass,  $A$ , is unchanged; this is characteristic of *beta decay*.) The new element neptunium is also radioactive, but is useless for practical purposes, since its half-life is only 2.3 days. One half of it decays within that time into the element plutonium,  ${}_{94}\text{Pu}^{239}$ , again by the emission of a beta particle. (See Fig. 2-10.)



The set of reactions just described occurs in all nuclear chain reactors which use natural uranium (99.29% U-238 and 0.71% U-235) as a fuel. Two examples of these are the 1943 Hanford reactor at the Columbia river in Washington, and the Brookhaven National Laboratory reactor in Long Island, N. Y. The new element plutonium is readily fissionable by *both* slow and fast neutrons, which makes it important for use in the atom bomb as well as in reactor technology. In addition, plutonium is a unique element (not an uranium isotope) and is easily separated by *chemical* means from other reactor products.

Another *fertile material* that can be converted into a fissionable fuel is thorium ( ${}_{90}\text{Th}^{232}$ ). The thorium process is used in some *breeder reactors* (reactors that produce more fissionable fuel than they consume) and may also become important if we should run short of uranium. The reactions, which are similar to those of the U-238-plutonium conversion are:



## NUCLEAR FISSION AND THE CHAIN REACTION

The new isotope of uranium, U-233, is also readily fissionable by both fast and slow neutrons. Thus we end up with at least three substances in our arsenal of fissionable fuels: U-235, U-233, and plutonium.

### Energy from Fission

The payoff of nuclear fission, in addition to the production of useful radio-isotopes, is its total energy output. This is truly astonishing and eclipses by far the energy yield of all chemical fuels.

But where does all this energy come from? It comes from the breakup of the U-235 nuclei, of course, and more specifically it originates from the *conversion of a tiny amount of mass into energy*. When the total mass of the fission fragments in a single fission is compared with that of the U-235 compound nucleus, it turns out that about 0.215 atomic mass unit (amu) is missing and not accounted for (1 atomic mass unit is defined as 1/16 of the mass of the oxygen atom,  $^{16}\text{O}$ ). This *mass defect* is less than one-fifth of the mass of a neutron or less than 1/10% of the mass of the original U-235 nucleus and, hence, may appear to be trifling. Yet, it appears from the famous *mass-energy equivalence relation*,  $E=mc^2$ , (formulated by Einstein in 1905) that a small amount of mass is the equivalent of a very large amount of energy. Einstein derived the formula from his relativity theory and could hardly have imagined, or ever intended, that some day actual mass-energy transformations would be accomplished in correspondence with the formula and on the gigantic scale of atom and hydrogen bombs.

The equation  $E=mc^2$  asserts that the energy equivalent of a material object is *equal to its mass (m) multiplied by the square of the speed of light (c)*. (The speed of light is thirty billion centimeters per second, or  $3 \times 10^{10}$  cm/sec.) Let us see what this amounts to for 1 gram (1/28 ounce) of any material, be it uranium, coal, sugar, or anything. Substituting in the formula,

$$E = mc^2 = 1 \text{ gm} \times (3 \times 10^{10} \text{ cm/sec})^2 = 9 \times 10^{20} \text{ ergs} = 9 \times 10^{13} \text{ joules.}$$

$$\text{Now } 1 \text{ joule} = 1 \text{ watt-second} = 1 / (3.6 \times 10^6) \text{ kilowatt-hour}$$

$$\text{Converting joules to kw-hrs: } \frac{9 \times 10^{13} \text{ joules}}{3.6 \times 10^6} = 2.5 \times 10^7 \text{ kw-hrs.}$$

*Thus one gram of anything converted into energy equals 25,000,000 kilowatt hours of energy.*

Now we said before that the mass defect in U-235 fission is about 0.215 amu which is approximately  $0.215/235=0.00091$  or 0.091% of the mass of the original U-235 atom (i.e., slightly less than 1/10% of the U-235 mass.) Hence, "burning up" a nuclear fuel of 1 gram of U-235 will result in the conversion of 0.00091 gm into energy. In kw-hrs, this is equal to:

$$0.00091 \text{ gm} \times 25,000,000 \text{ kw-hrs/gm} = 22,600 \text{ kilowatt hours of energy.}$$

*One pound (454 grams) of U-235 fuel produces  $454 \times 22,600$  – approximately 10,000,000 (ten million) kilowatt hours of energy (Fig. 2-11). Assuming a*

## NUCLEAR ENERGY AND POWER REACTORS

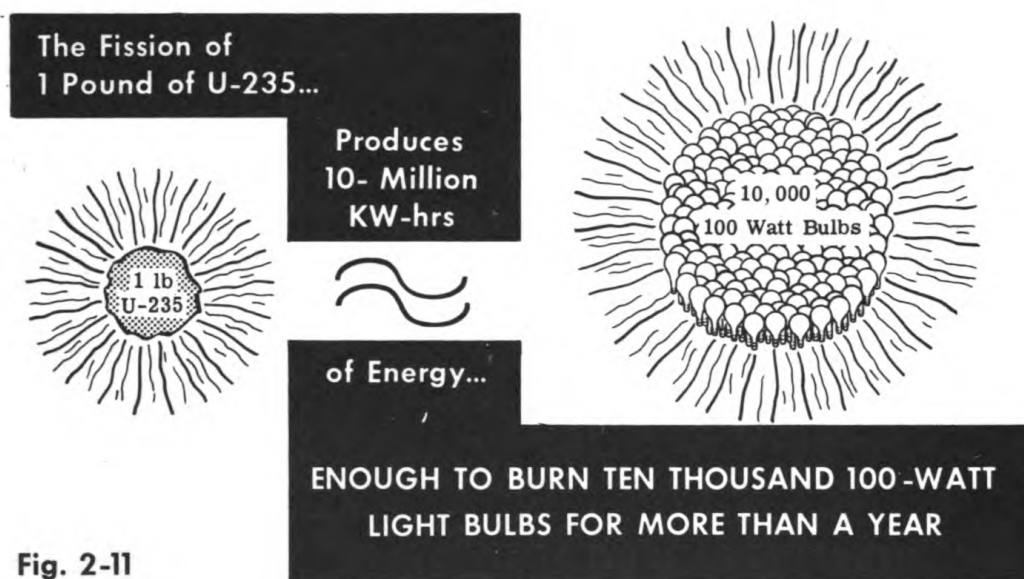


Fig. 2-11

standard electrical power cost of about  $\frac{1}{2}$  cent per kw-hr, the *energy value of U-235 is \$50,000 per pound*. Despite these favorable figures, however, it has been found that the cost of building and maintaining a nuclear power plant in the United States is so high that the cost per kw-hr cannot as yet compete with that of coal and other conventional fuels.

The energy of nuclear particles is usually expressed in millions of electron volts (Mev). By substituting in the formula  $E = mc^2$  it is easily shown that the energy equivalent of 1 atomic mass unit is approximately 931 Mev. Hence, the mass defect of 0.215 amu during the fission of U-235 produces about  $0.215 \times 931$ , or 200 Mev of energy per fission, a figure that we gave earlier.

### Binding Energy

It is of interest to note that a mass defect occurs not only in the fission of U-235, but is *present in the nuclei of all stable atoms*. If, for example, we compare the mass of the helium nucleus with the combined mass of the two protons and two neutrons that make it up, we find that the helium nucleus is actually lighter than the sum of its parts, the mass defect being about 0.03033 amu. This equivalent to  $0.03033 \times 931$ , or about *28 Mev of energy*, and represents the *binding energy* of the nucleus. To tear the nucleus apart, at least this amount of energy must be supplied. Moreover, the greater the mass defect, the greater the binding energy, and the more stable the nucleus of the atom. It turns out that the binding energy per nucleon is greatest for mass numbers around 50, reaching 8.71 Mev/nucleon for chromium ( $^{52}_{24}\text{Cr}$ ), and dropping off both at the light and heavy end of the periodic table. (The binding energy for U-235 is 7.6 Mev/nucleon.) This explains why nuclear fission (as well as fusion) always produces middle-of-the-table elements,

## NUCLEAR FISSION AND THE CHAIN REACTION

which because of their greater binding energies—are more stable. Energy transformations always proceed in the direction of greatest stability.

### Nuclear Chain Reaction

Since each nuclear fission produces from two to three neutrons capable of fissioning other uranium atoms, a wild-fire chain reaction is possible. To make the reaction self-sustaining it is really only necessary that at least *one* of the neutrons released by fission produces another fission; that is, *the ratio of "daughter" neutrons produced by fission to the "parent" neutrons originally present, called the multiplication factor ( $k$ ), must be at least 1.* (Actually, it must be somewhat greater than 1 to compensate for neutron losses.) The value of the multiplication factor,  $k$  (which depends on the balance between the relative production and loss of neutrons) determines whether or not a chain reaction takes place and what kind it will be. If  $k$  is less than 1, a chain reaction cannot take place. If  $k$  equals 1, a chain reaction will proceed with constant neutron flux, as in a controlled nuclear chain reactor. Finally, if  $k$  is greater than 1 (by more than the amount necessary to make up for losses) the neutron flux constantly increases with time and an uncontrolled, violent chain reaction takes place, as in the atom bomb.

### Nuclear Fuels

The value of  $k$ , and hence the type of chain reaction, depends among other things on the nuclear fuel used in the reaction. We have seen that U-238 is occasionally fissioned by *fast* neutrons, while U-235, U-233 and plutonium-239 are fissionable by *both slow and fast* neutrons. We can immediately eliminate pure U-238 as a nuclear fuel, because the average U-238 fission neutrons are too slow to fission other U-238 atoms and, hence, a chain reaction cannot take place. Moreover, U-238 does not fission easily, but either scatters or captures most of the neutrons colliding with it. The other three fuels, U-235, U-233 and Pu-239, are equally useful for either slow or fast neutron chain reactions.

### Uncontrolled (Fast) Chain Reaction

Consider first the type of chain reaction that takes place, for example, in substantially pure U-235, the fissionable fuel most generally available. A single neutron colliding with a U-235 nucleus will fission it, giving rise to two or three fast neutrons in the process. In the absence of any other material and assuming that all released neutrons eventually find other U-235 targets, two to three additional U-235 atoms will be split, and from 4 to 9 additional neutrons will be released in this "third generation" alone. (As example, 7 neutrons are shown in Fig. 2-12.) Theoretically, if all of the neutrons released per fission go on to split other U-235 atoms, the multiplication factor ( $k$ ) is 2.5, and the chain reaction multiplies at a geometric progression with a ratio of 2.5. The *average* number of neutrons in such a progression spreads like this:

## NUCLEAR ENERGY AND POWER REACTORS

In a **FAST FISSION REACTION** each neutron that splits a U-235 nucleus frees two to three additional neutrons, which in turn split more U-235 nuclei. An astronomical number of atoms are fissioned in less than a billionth of a second.

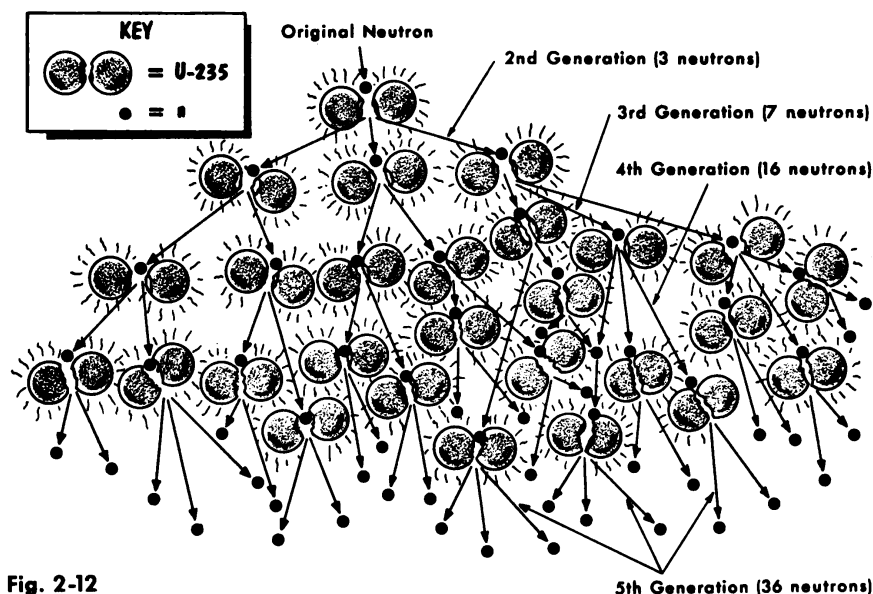


Fig. 2-12

1, 2.5, 6.25, 15.6, 39, 97.7, 244, 610, 1526, 3815, 9537, etc.

In other words, the tenth generation would number 3815 fissioned U-235 atoms that would send out 9537 additional neutrons to produce further fissions. Since each of these would start a new series, the twentieth generation would number approximately 36,000,000 fissioned atoms and, say, the sixtieth generation would number approximately a *trillion trillion fissioned atoms* (more exactly  $0.752 \times 10^{24}$  atoms), which is equal to about 10 ounces of U-235. Yet, since each generation of fissions takes only about a trillionth ( $10^{-12}$ ) of a second, the explosion of sixty generations or 10 ounces of U-235 take place in *sixty trillionths* ( $60 \times 10^{-12}$ ) of a second accompanied, of course, by the release of a fantastic amount of energy.

### Critical Mass

The assumptions on which we based our portrayal of the fast fission reaction are not quite correct, however. First of all, the U-235 is never 100% pure in practice. Atoms of U-238 and other elements, which absorb or scatter some of the fission neutrons, are always present. Other neutrons may never find a U-235 target nucleus, or their energies may be so low that they are either *captured or scattered* by the atoms. Finally, and most important, quite a few

## NUCLEAR FISSION AND THE CHAIN REACTION

neutrons near the surface of the fissionable material, simply *leak out or escape* without ever fissioning any U-235 atoms. All these factors decrease the actual multiplication factor to a figure considerably lower than the theoretical value of 2.5 assumed in our example.

The *escape of neutrons* from the surface of the fissioning mass is *proportional to the total surface area*. The number of neutrons produced, on the other hand, is proportional to the number of fissionable atoms, or equivalently, to the *total volume of the fissionable mass*. To reduce the loss of neutrons to a minimum, therefore, we must use a geometrical configuration that provides minimum surface for a given volume or mass of material. As you may know from soap-bubble blowing days, soap bubbles always try to attain minimum area by forming themselves into spherical shape. The sphere, therefore, answers our requirements of maximum volume for minimum surface, although other shapes are sometimes used for practical reasons.

Assume, for example, that we start with a small sphere of U-235, about the size of the pea. This small mass will produce relatively few fission neutrons and most of these will escape from the surface, because the *mean free path* between fission collisions is larger than the diameter of the sphere. As we increase the size and mass of the U-235 sphere, its surface goes up as the *square* of the radius, but its volume goes up as the *cube* of the radius. As a result progressively more fission neutrons are produced within the volume of the U-235 sphere and progressively fewer neutrons leak out from the surface. At a certain *critical radius* of the sphere, the production of neutrons by fission is just *equal* to the sum of neutrons lost by escape from the surface and neutrons required to cause an equal number of fissions. The multiplication factor then equals unity ( $k = 1$ ), and the system is said to *go critical*, have *critical mass* or *critical size*. If the spherical mass is made just a little larger than this critical value, a self-sustaining, though uncontrolled, chain reaction will take place. This is not only true for the explosive chain reaction of pure U-235 or plutonium in the atom bomb, but there is a *critical size (or mass) for any device containing fissionable material* at which a self-sustaining chain reaction occurs.

### The Atom Bomb

If we were to assemble a sphere of U-235 or plutonium of slightly overcritical mass, any stray neutron (from cosmic rays, for example) would start the fission chain reaction, but the "explosion" would be very inefficient. The heat of the fission reaction would instantly force the material apart and its size would become subcritical before any sizable percentage of atoms in the mass would have fissioned.

To obtain an "efficient" explosive chain reaction, it is necessary to hold the critical mass together long enough to split a relatively large percentage of the available fissionable atoms. This is achieved in the atom bomb by a heavy, dense material, known as the *tamper*.

## NUCLEAR ENERGY AND POWER REACTORS

As shown in Fig. 2-13, a slightly imaginative sketch of the construction of an atom bomb, a subcritical, spherical mass of U-235 or plutonium is contained in the center of a large spherical outer casing. The space between the fissionable mass and the outer casing is filled by wedges of conventional explosives. A number of electrical detonators that can be fired simultaneously are placed around the sphere. If this is done, an enormous pressure wave (*implosion*) travels *inward* and compresses the small sphere of fissionable material equally on all sides. As a result, the subcritical mass is compressed into a smaller, denser sphere that goes instantly critical. This is an interesting variation of the critical mass principle, inasmuch as the mass remains the same and the size actually *decreases*. What happens is that the *density* (mass per unit volume) of the fissionable material *increases* as it becomes squeezed into a smaller volume, and thus there is a greater mass of fissionable atoms *per unit volume*. Stated in a different way, the increase in density reduces the mean free path of the neutrons between fissions to a critical value.

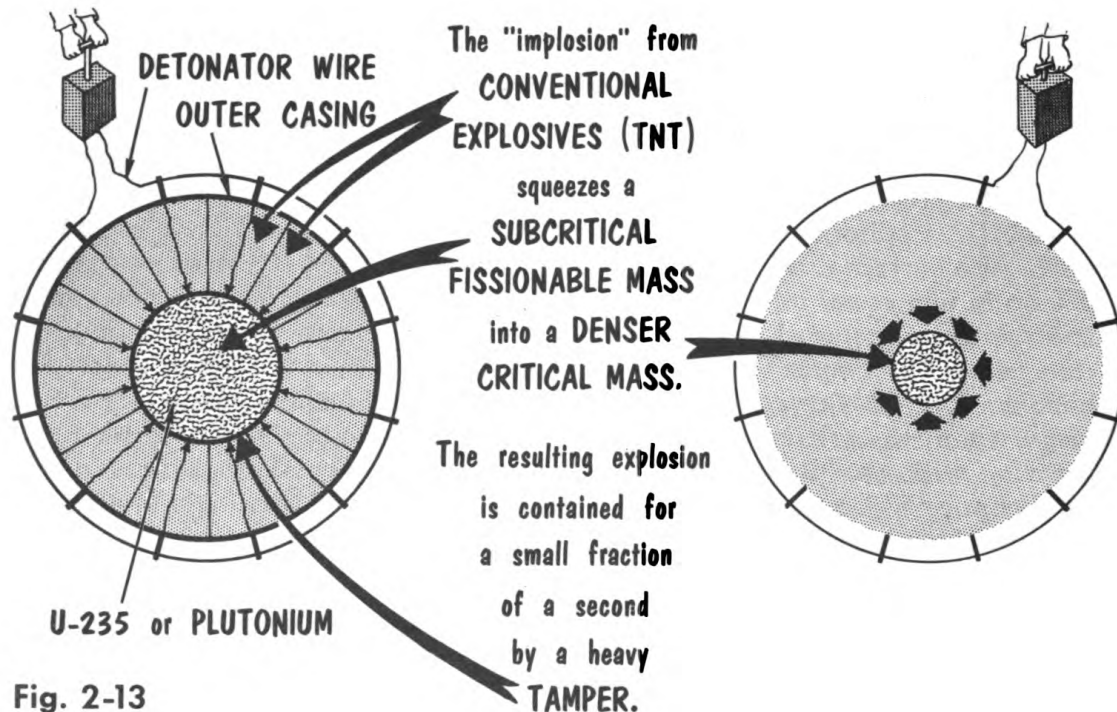


Fig. 2-13

As soon as the fissionable mass in the A-bomb is compressed to critical size, it explodes. The explosion is contained for a few microseconds by the tamper, which helps to build up the temperature to more than  $10,000,000^{\circ}\text{C}$  and the pressure to enormous values. In addition to delaying the expansion of the bomb and thus assuring an efficient reaction, the tamper also reflects many neutrons back into the bomb, which further multiplies the number of fissions. The final result is the familiar ball of fire (Fig. 2-14) that radiates visible, infrared, ultraviolet, and X-rays in all directions. This is accom-

## NUCLEAR FISSION AND THE CHAIN REACTION

panied by a mechanical blast wave equal to at least 20,000 tons of TNT and by a lethal flash of neutron and gamma radiation, produced by radioactive fission products.

Start seen from 6 miles



Fig. 2-14

### OF AN ATOMIC FIREBALL

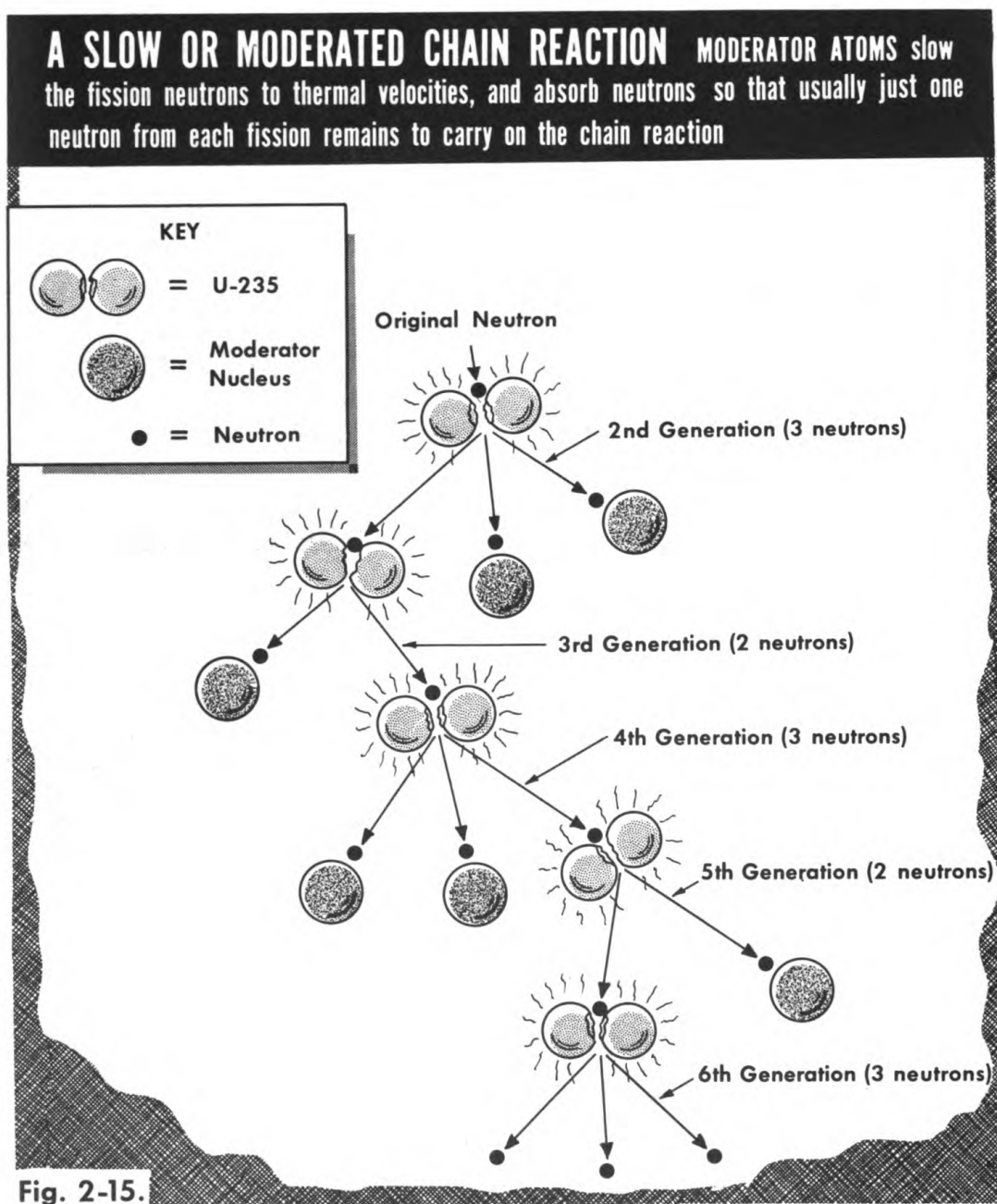
#### Slow (Moderated) Chain Reaction

Slow-moving neutrons are more effective in fissioning atoms of U-235, plutonium, or natural uranium, the latter being a mixture of 99.29% U-238 and 0.71% U-235 isotopes. Since most nuclear chain reactors use either natural or U-235 enriched uranium fuel, the slow chain reaction is the type most useful and most easily controlled in industry. As we have seen, however, the neutrons produced by any type of fission are always fast moving, having energies around 2 Mev. For a slow chain reaction to occur, therefore, the uranium must be mixed with a *moderator* that will slow down the fast fission neutrons to thermal energies. (Thermal energies are in the order of 0.025 electron volt, corresponding to the energies of gas molecules moving at ordinary temperatures.) It has been found that substances of *low atomic weight*, such as beryllium, graphite (carbon), and heavy water are most effective in slowing down or *moderating* the fission neutrons to thermal velocities through numerous elastic billiard-ball collisions.

When a moderator is mixed with the uranium fuel, the moderator atoms will compete, of course, with the uranium for the supply of available neutrons. A number of the "daughter" neutrons in each generation will either be absorbed or scattered, as shown in Fig. 2-15, cutting down the multiplication factor,  $k$ . If the right proportions of uranium fuel and moderator are chosen, a delicate balance is achieved, where (after many generations) the multiplication factor steadies down close to unity ( $k = 1$ ). This means that only one neutron from each fission remains, on the average, in each generation to propagate the chain reaction. This results in a constant neutron flux.

Consider the life history of some typical fission neutrons produced in a reactor consisting of a pile of natural uranium fuel rods imbedded in a graphite block that serves as moderator. Some of the fission neutrons in each generation have sufficient energy to produce *fast fissions*, both in U-238 and

## NUCLEAR ENERGY AND POWER REACTORS



U-235 atoms, thus swelling the total number of available neutrons by a small factor (about 3 %). From now on, however, the neutrons encounter nothing but hard luck and their fate reads like the well-known verse about the ten little Indians. The fast neutrons are rapidly slowed down to thermal energies by collisions with moderator atoms, but before this process is completed, quite a few neutrons are literally captured by U-238 nuclei, which have an appetite (called *resonance*) for moderately slow neutrons of about 6 to 7 electron volts energy.

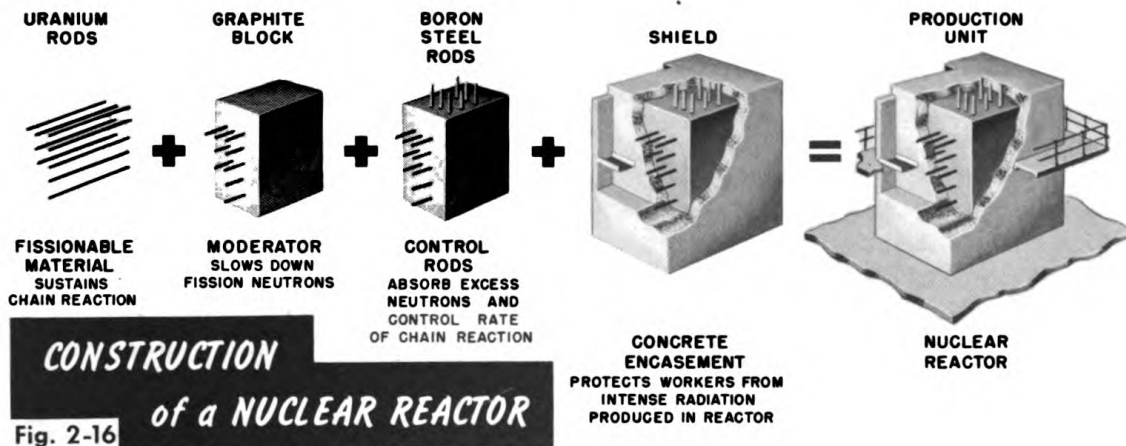
## NUCLEAR FISSION AND THE CHAIN REACTION

Of the remaining neutrons that reach thermal energies, an additional toll is taken by absorption into atoms of the moderator, those of the cooling liquid and those of other "poisons" present, as well as the more legitimate absorption into uranium atoms that produce further fissions. Moreover, during the entire process, neutrons that stray too close to the surface of the reacting mass, simply *escape* and are lost to the reaction.

It is no surprise, therefore, that of the 2.5 fast neutrons originally produced by each fission, little more than a solitary neutron survives to produce additional fissions in each generation. Evidently, when calculating the multiplication factor,  $k$ , for a practical reactor all these factors must be taken into account. Allowance must also be made for the reduction in  $k$  due to the accumulation of fission products (called *poisons*) as the original fuel charge is used up. When  $k$  becomes too low, refueling becomes necessary.

### Simple Nuclear Reactor

Let us now look for a moment at the construction of a simple nuclear reactor (Fig. 2-16), consisting of a natural uranium-graphite "pile," similar to that



used by the early reactors in Chicago and Hanford. As shown in the illustration, the reactor is essentially a large graphite block, serving as moderator, into which the fissionable natural uranium rods are imbedded. A certain amount of *excess reactivity* is built into the reactor (i.e.,  $k$  is made greater than 1) to assure the proper neutron flux for the desired power level, to overcome the poisoning effects of the fission products, and to compensate for the burnup of uranium fuel during reactor operation. To avoid dangerous radiation or an explosion, this excess reactivity must be accurately controlled. This is easily done by inserting into the reactor adjustable *control rods*, made of cadmium or boron, which tend to *capture thermal neutrons*, reducing the total neutron flux. By regulating the depth to which these control rods are inserted into the pile, it is possible to maintain a multiplication factor of unity ( $k = 1$ ) at the desired power level.

## NUCLEAR ENERGY AND POWER REACTORS

Finally, the operating personnel of the reactor must be protected from the intense radiation produced in an operating reactor by a suitable *shield*, which may be ordinary or heavy water or a concrete encasement. If power is to be withdrawn from the reactor, some form of cooling must also be provided, either by water or by a liquid metal, such as sodium or mercury.

### 3: BASIC TYPES OF NUCLEAR REACTORS

Within the brief span of 15 years nuclear reactors have proven themselves an indispensable research tool throughout the world. In, perhaps, another 10 years they will become competitive with coal, oil, and other fuels as electric power producers. Despite some discouragement in recent years about the high cost of nuclear power, the long-term outlook is favorable, especially as increasing experience is gained from various experimental reactors and pilot plants. Moreover, the next 10 to 15 years may be considered an interim period, during which ways may be found to exploit directly the energy from uranium fission or, perhaps, even master the secret of controlled hydrogen-fusion reaction.

#### Reactor Classification

Nuclear chain reactors can be classified in several different ways, depending on the type and arrangement of fuel, moderator, and coolant used, and on the speed (energy) of the neutrons sustaining the fission reaction. *Moderators*, used to reduce the neutron energy, are primarily graphite, light water and heavy water (using the heavy isotope of hydrogen, deuterium). Active fuel materials may be either natural uranium,  $U^{235}$ -enriched uranium, plutonium ( $Pu^{239}$ ) or  $U^{233}$ . As we have seen, the last two are high-cost artificial reactor-produced elements.

The arrangement of moderator and fuel provides a further basis for classification. In a *heterogeneous solid-fuel* reactor the fuel is in the form of lumps embedded in a regular pattern (*lattice*) within the moderator. In a *homogeneous liquid-fuel* reactor the fuel and moderator are intimately mixed in the form of a solution, alloy or chemical compound. Reactors operated above minute power levels must use some form of cooling to keep the temperature down. Light water, heavy water, liquid metals, or forced-gas cooling are generally used.

Reactors are further classified by the speed or energy of the neutrons that cause fission. Neutrons of less than about 0.1 ev (electron volt) are called *slow or thermal*, neutrons of about 1 to 1000 ev are known as *intermediate or resonance* (because of the occurrence of resonance capture rather than fission), and neutrons with energies greater than about 1000 ev (0.001 Mev) are called *fast*. A *fast reactor* does not use a moderator to slow down the fission neutrons.

Finally, reactors are often classified according to their purpose. *Research reactors* are built primarily to test new designs and provide a copious source of neutrons and gamma rays for physical, biomedical, and industrial research, as well as for radioisotope manufacture. *Production reactors* are built to manufacture fissionable materials by conversion of non-fissionable (*fertile*) materials. Reactors capable of providing useful electrical power outputs are known as *power reactors*. *Breeder reactors*, capable of producing more fissionable fuel than they consume, may be classed either as production or power reactors, depending on their ultimate purpose.

## NUCLEAR ENERGY AND POWER REACTORS

We shall confine ourselves in the present chapter to the description of a few basic types of research reactors, which are the experimental forerunners of power-producing reactors. Since many more types of research reactors have been built than have ever been tested for power production, the research reactors present a convenient design reservoir for experimental power reactors. The construction of power reactors has proceeded somewhat hesitantly in this country, largely because of the high costs involved, and it is difficult to predict at this time which design will eventually prove itself most economical and efficient. It is of interest, therefore, to study some examples of *four basic types* of reactors, from which most power-reactor designs originate. These are: *graphite-moderated* reactors, *light-water moderated* reactors, *heavy-water moderated* reactors, and *homogeneous fuel* reactors. (The first three types use *heterogeneous* fuel.)

### Graphite-Moderated Reactors

The heterogeneous, graphite-moderated reactor, fueled with natural uranium (U-238), is the Model T of the reactor industry. Graphite/natural-uranium reactors were the first type to be built in the United States and they are generally characterized by large size and high cost per unit of neutron flux. The core of a typical graphite-moderated reactor is a cube measuring about 25 feet on a side, that requires some 500 tons of graphite and 100 tons of uranium. If operated with a heat output of about 30,000 kilowatts, such a reactor would produce a maximum thermal-neutron flux of about  $5 \times 10^{12}$  (five-thousand billion) neutrons per square centimeter per second. The cost of a graphite/natural-uranium reactor runs anywhere from 5 to 25 million dollars, which is considerably more *per unit* neutron flux than that of enriched-uranium reactors. Since enriched uranium is now readily available, the large and costly natural-uranium reactor has become rather unattractive, and it is unlikely that any more of them will be built. Most existing natural-uranium reactors are being converted for use with enriched uranium fuel, and all new graphite-moderated reactors use enriched fuel.

Historically, the first self-sustaining nuclear chain reaction was achieved on December 2, 1942 in a natural uranium-graphite reactor, the Chicago Pile (CP-1) at Chicago University. The maximum power of the Chicago pile was two hundred watts, but this was rapidly stepped up in later reactors at the Argonne National Laboratory (CP-2 and CP-3) and at Hanford, Wash. A natural-uranium/graphite reactor (X-10 pile), placed into operation in 1943 at the Oak Ridge National Laboratory, used 35 tons of uranium and 620 tons of graphite to produce a power level of about 3800 kilowatts and a thermal-neutron flux of about  $10^{12}$  neutrons/cm<sup>2</sup>-sec. Finally, the most modern and largest graphite-moderated research reactor, operating since 1950 at the Brookhaven National Laboratory (Upton, Long Island, N.Y.), attains (heat) power outputs up to 30,000 kilowatts with a thermal-neutron flux of about  $5 \times 10^{12}$  neutrons/cm<sup>2</sup>-sec. The design of the Brookhaven reactor is based upon the experience gained during the war years with the Oak Ridge and Hanford reactors, and it is typical of all graphite-moderated reactors.

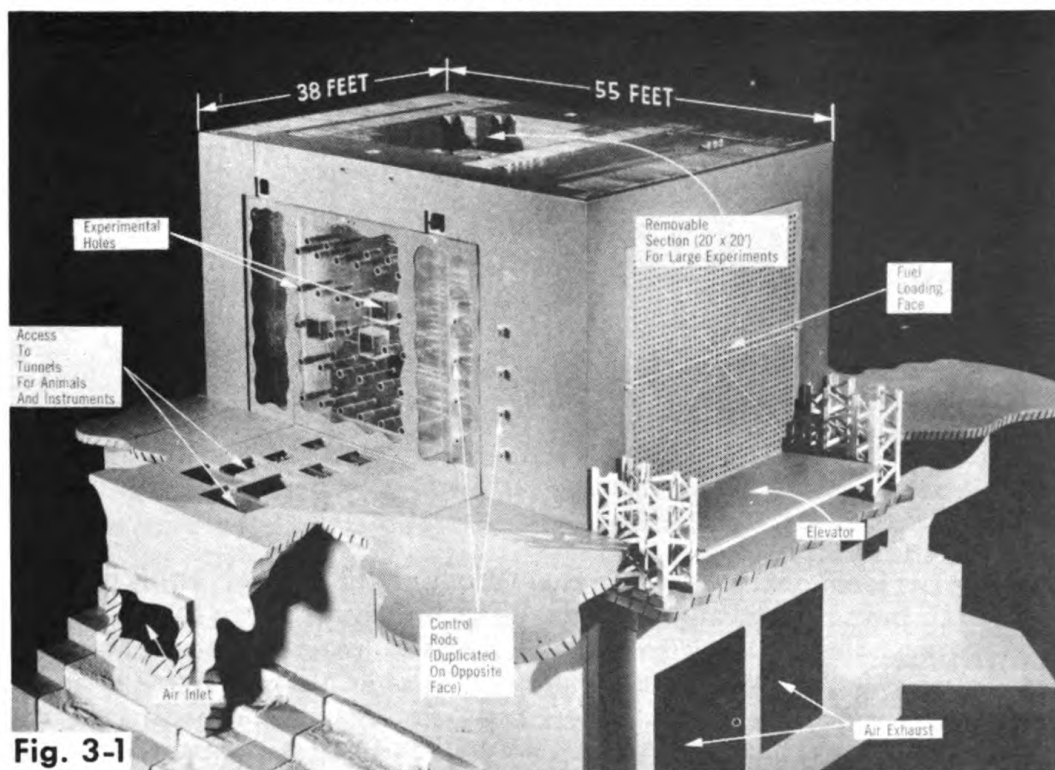
## BASIC TYPES OF NUCLEAR REACTORS

### The Brookhaven National Laboratory (BNL) Reactor

The Brookhaven National Laboratory (BNL) reactor is of the forced-air-cooled, natural-uranium graphite-moderated, thermal-type reactor and is designed specifically for fundamental research programs. The bulky graphite-moderated core is an advantage for this purpose, since it provides large research areas adjacent to the reactor. Special experimental facilities permit exposing various materials to high-intensity neutron bombardment, beam-radiation experiments, and the production of radioisotopes. To obtain the required neutron flux density of about  $5 \times 10^{12}$  neutrons/cm<sup>2</sup>-sec for these experiments, a heat level of 28,000 to 30,000 kilowatts is provided.

The basic structure of the Brookhaven reactor is a 25 foot graphite cube, which is separated into two halves by an inlet air gap, 2  $\frac{3}{4}$  inches wide, in the vertical east-west plane. (See Fig. 3-1.) Sixty thousand graphite bricks with a total weight of 700 tons make up the core, which is penetrated in the north-south direction by 1368 round parallel fuel channels, spaced 8 inches between

### *Largest Graphite-Moderated Research Reactor in the United States*



*A Cut-Away Model of the BROOKHAVEN REACTOR*

## NUCLEAR ENERGY AND POWER REACTORS

centers (Fig. 3-2). The fuel is in the form of uranium slugs, 4 inches long and about 1 inch in diameter, which are contained in aluminum cartridges 11 feet long, 33 to a cartridge. The cartridges are finned on the outside to increase heat transfer and are filled with a helium gas to provide an inert atmosphere for the uranium. Helium lines from the cartridges feed to a central point and serve the double purpose of indicating leaks in individual cartridges and carrying off gaseous fission products (*poisons*).

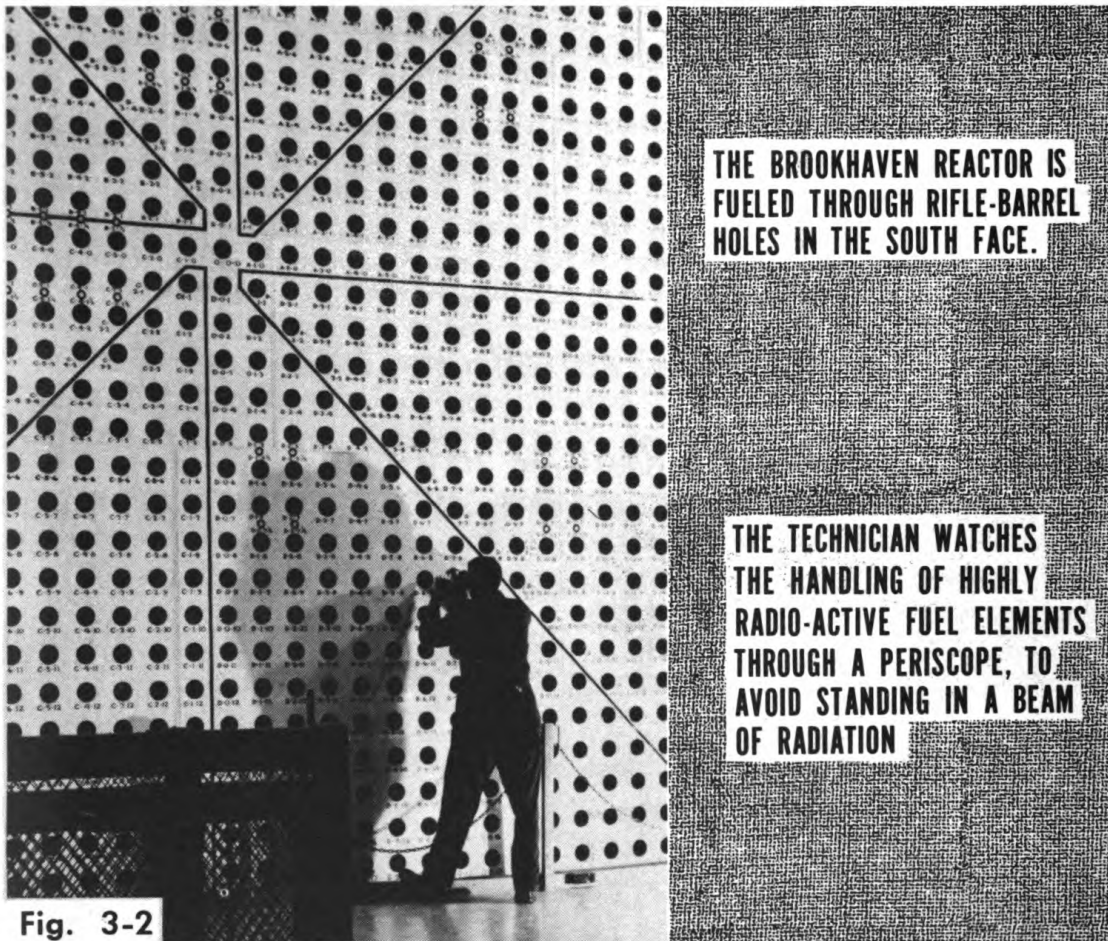


Fig. 3-2

### Fuel Loading

The reactor is loaded with uranium fuel through "rifle-barrel" holes provided in the south face. An elevator enables the technician to move to any level of fuel-charging holes. The critical mass of the BNL reactor is about 50 tons of natural uranium, but considerably more fuel is required to provide sufficient excess reactivity for the desired power level. For example, a loading of 33 by 33 channels (1089 channels) requires 2176 cartridges, containing 71,808 uranium slugs that weigh 2.58 lbs each, making a total weight of uranium of 185,000 pounds, or 92.5 tons. A loading of 35 by 35, or 1225 fuel

## BASIC TYPES OF NUCLEAR REACTORS

channels requires 80,784 uranium slugs, weighing 104 tons. Despite these huge quantities of fuel, the reactor is none too efficient, attaining a relatively low *specific power* per pound of natural uranium. It has been converted for use with highly enriched uranium and now contains about 57 kilograms of uranium-235.

### Cooling

The BNL reactor is cooled by a stream of air, which is drawn through the central inlet air gap and flows out through the fuel channels in both directions, removing heat from the aluminum cartridges and the graphite. Five 1500-hp fans draw the cooling air through the reactor at the rate of 750 tons per hour, and exhaust it through a 320-foot stack. Airspeeds reach several hundred miles per hour in the fuel channels. The air is filtered both before and after leaving the reactor to remove any particles that might become radioactive under neutron bombardment. The air is also cooled by water to reduce its volume before reaching the fans.

### Shielding

The graphite cube and air chambers are enclosed in a shield, consisting of five-foot thick steel and concrete walls, which have a density about double that of ordinary concrete. On the north and south sides large air chambers (plenums), are provided between the graphite and the concrete. The shield is highly effective and limits the radiation exposure of personnel during an eight-hour period to about 5 milliroentgens, which is far below permissible tolerance levels.

### Control Rods, Safety, and Instrumentation

The BNL reactor is controlled by means of 16 control rods, made of a steel alloy that contains a small amount of boron. The 26-foot boron-steel rods are run into the pile diagonally from the east and west faces so that the sides and top are left free for research. Of the 16 horizontal rods, 14 are "emergency" rods for shutting down the reactor and two are "regulating" rods for controlling the operating power. The regulating rods are driven by independent induction motors and gearing, which permits accurate positioning of the rods at speeds of either 5 or 0.05 inches per second. Each emergency rod is driven by a separate electric-motor-driven hydraulic system for independent control. As an extra safety measure, a mechanical flywheel running at 1765 rpm is coupled between the electric motor and the hydraulic pump of each emergency rod. The entire control-rod system is capable of handling an excess multiplication factor ( $k$ ) of about 0.035, which is more than sufficient to reduce the value of  $k$  to less than 0.99 for rapid shutdown of the reactor.

The 16 motor-driven control rods are used for normal start-up, operation, and shutdown of the reactor, as well as for emergency shutdowns. Any one of the 56 signals in an emergency shutdown system will cause all the rods to

## NUCLEAR ENERGY AND POWER REACTORS

be run into the reactor at full speed, thus shutting it down. If the electric power should fail, the stored energy in the constantly rotating flywheels on each motor shaft quickly drives the rods in. To supplement the control rods, four *boron shot wells* are provided, into which boron steel balls can be dropped from the control room for emergency shutdown. Finally, an additional safety system is provided in the form of a liquid "poison" (trichlorobenzene), which can be released to flood pneumatic tubes running throughout the reactor.

A variety of instruments indicate and record the level of neutron flux in the reactor to guide the operator, who must actuate the alarm and emergency-shutdown systems and record reactor activity. Because of the time required to slow down the fission (prompt) neutrons and the effect of the delayed neutrons, a reactor rises to power at a slowly decreasing rate, which eventually reaches a stable value. The *period of a reactor* is the time required for the neutron flux to attain this stable rate of increase in power. This is measured in the BNL reactor by a *graphite ionization chamber*, consisting of a set of graphite disks coated on both sides with boron. As the neutrons collide with the boron atoms, the latter throw out an equal number of *recoil alpha particles* that ionize the gas in the chamber and produce a current that is proportional to the neutron flux. Figure 3-3 shows an early system used for indicating reactor power and period at Brookhaven.

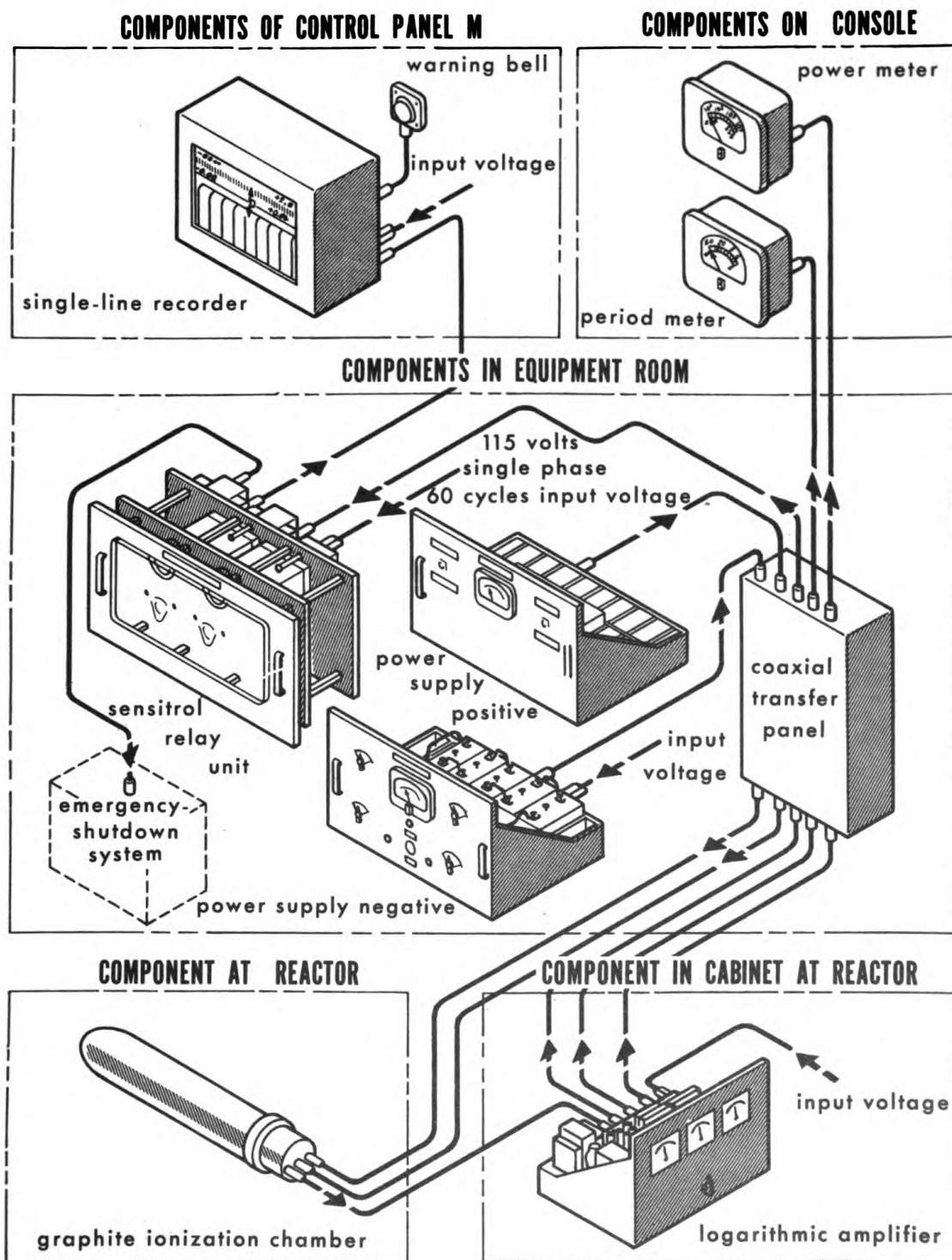
The current from the ionization chamber is proportional to the *logarithm* of the neutron flux. This permits the same power meter to be used for indicating a wide range of power and also allows indication of the reactor period on a logarithmic *period meter*. If the reactor period is too short (that is, the reactor rises to power too fast), a *trip circuit* (Sensitrol relay) is energized to sound a warning bell and actuate the emergency shutdown system.

Since neutron detection instruments and indicators have a limited range, additional power-indicating systems are provided in the Brookhaven reactor. At low powers, from shutdown to about 100 watts, the reactor power is indicated by a *neutron counting system*, using a boron fluoride or boron-lined neutron counter whose output is proportional to the neutron flux. At intermediate powers, up to about 300 watts, the reactor power is indicated by a *neutron counting rate system*, which utilizes a *fission chamber* lined with U-235. When thermal neutrons strike this chamber, they produce strongly *ionized fission fragments*, which can be counted by conventional counter circuits. Finally, a *galvanometer system* was initially used to indicate reactor power at high-level operation up to full power. The primary element for this system was a *graphite differential ionization chamber*, identical with that described for the period (logarithmic) system.

Additional instruments and controls indicate the radiation levels of the air in the stack and building, and provide protection against excessive levels in any of the measured quantities. The controls and instruments are brought together at an operating console in the control room.

## BASIC TYPES OF NUCLEAR REACTORS

**THE LOGARITHMIC SYSTEM INDICATES THE REACTOR PERIOD AND POWER**



**Fig. 3-3**

## NUCLEAR ENERGY AND POWER REACTORS

### Costs

The total construction cost for the Brookhaven reactor is estimated at \$25,500,000, out of which some \$9,300,000 were spent for the reactor proper. The reactor building cost \$3,000,000; the laboratories \$5,800,000; the cooling system \$3,800,000; and the remainder of \$3,600,000 was spent on site development, radioactive waste disposal facilities, electrical facilities and miscellaneous items. The yearly cost of the operating staff is estimated at \$285,000.

### Light-Water-Moderated Reactors

We turn now from the obsolescent natural-uranium reactors to reactors fueled with uranium enriched in U-235. The use of U-235 eliminates most of the U-238 and increases the multiplication factor of a reactor to such an extent that the critical mass of the fuel is reduced to a few pounds, and the size of the reactor to dimensions in the order of 1 to 3 feet. This lowers the cost and increases versatility.

The first type of enriched fuel reactors we shall discuss are the *light-water-moderated heterogeneous* reactors. These come in two kinds, *pool reactors* and *tank reactors*. The pool reactors are so named because they consist essentially of a U-235-enriched reactor core immersed in a large pool of water. This arrangement is satisfactory for low-power reactors (up to about a thousand kilowatts), where the heat produced is taken care of by convective water cooling. As the power is stepped up, however, convective cooling is no longer sufficient and, moreover, radioactive materials produced by constant irradiation of the water begin to rise to the surface. To avoid these problems, higher-powered light-water reactors are always enclosed in a *tank*, through which water is pumped under pressure to carry away the heat. We shall have more to say about these *pressurized-water reactors* in the next chapter, but for the present we shall confine ourselves to the *open-pool* type. The latter are used in a variety of low power applications and have the chief advantages of *low cost, safety, accessibility, and flexibility*.

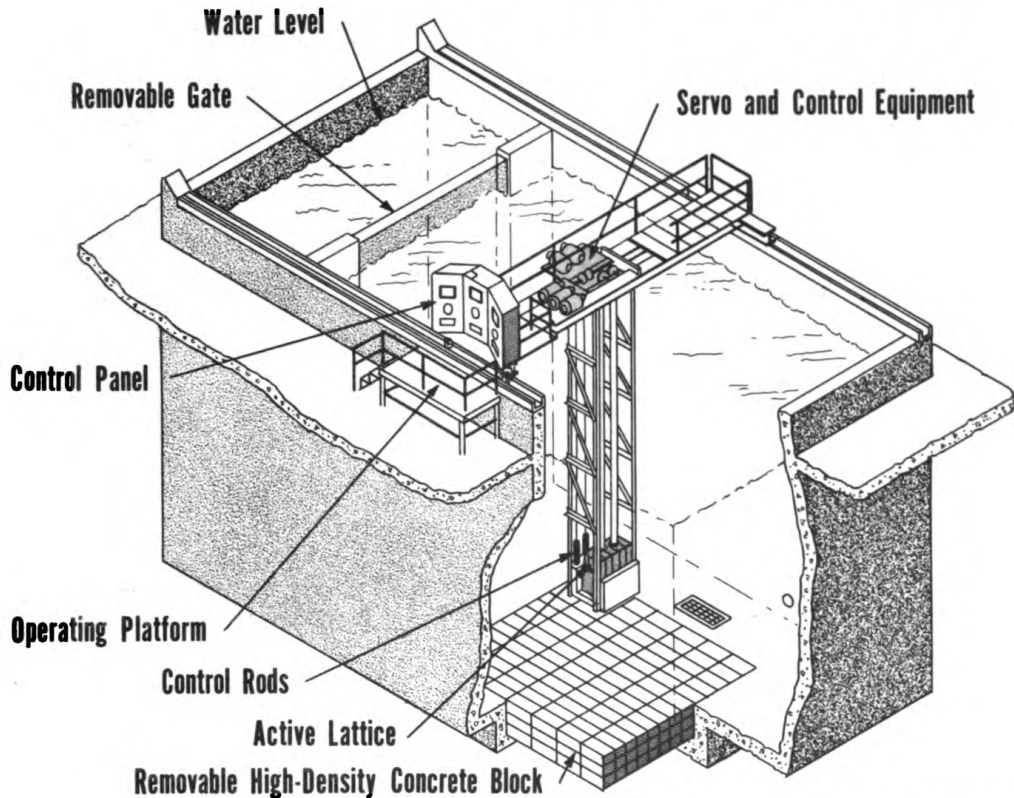
### Bulk Shielding Reactor (BSR)

The prototype of the light-water-moderated, enriched fuel pool reactors is the Bulk Shielding Reactor (BSR) at the Oak Ridge National Laboratory in Tennessee. This reactor, placed into operation in December 1950, resulted from the development of the Materials Test Reactor (MTR), operating at the Arco (Idaho) Reactor Station. The latter is one of the largest light-water-moderated reactors and produces the most intense neutron flux available from this type of reactor.

The bulk shielding reactor (BSR) is essentially a lattice of enriched uranium fuel elements suspended from a movable bridge in a pool of water. The all-encompassing water serves the four separate functions of moderator, neutron reflector, coolant, and shield. This quadruple combination of usually

## BASIC TYPES OF NUCLEAR REACTORS

### ***BULK SHIELDING REACTOR (BSR)***



***This is a light-water moderated pool reactor of the heterogeneous enriched-fuel type.***

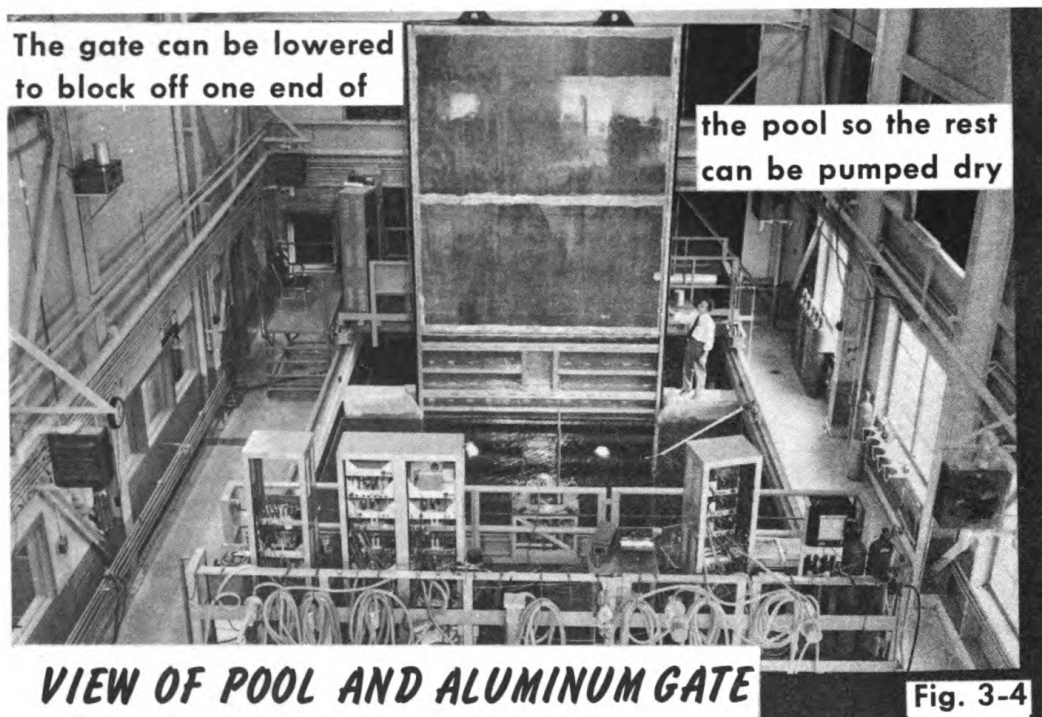
Fig. 3-3A

separate reactor components is responsible for the comparatively low cost of the pool-type reactor.

The pool of the BSR is 40 feet long, 20 feet wide, and 20 feet deep; it is provided with a well  $14 \times 14 \times 5$  feet (deep) at the north end. An aluminum gate can be lowered between guides near the south end of the pool, thus blocking off this end and permitting the rest of the pool to be pumped dry. Shielding experiments (from which the reactor derives its name) may then be conducted on the dry side of the gate, while the reactor is moved close to the other side. Figure 3-4 is a view of this gate ready to be lowered into position.

Removable concrete blocks are provided as part of the pool floor. The blocks have a high density (3.2), thus cutting down on neutron and gamma radiation. The reactor is frequently operated with all blocks removed to provide space beneath the core for materials being tested.

## NUCLEAR ENERGY AND POWER REACTORS



The reactor and control (servo) equipment are mounted on a movable bridge that spans the pool. A control room from which the reactor is operated and in which all controlling, indicating, and recording instruments are contained is located about eight feet from one side of the reactor pool. An instrument bridge, similar to the reactor bridge, also spans the pool. As shown in Fig. 3-5, a cart traveling on rails on the bridge permits lowering various measuring instruments to any point in the pool.

Access to the reactor is practically unrestricted, permitting the irradiation of large and bulky objects and the use of large instruments against the reactor face. In addition, the use of water as both shield and coolant allows direct visual observation of the reactor core during operation, which is of advantage for training reactor personnel.

### Reactor and Fuel Elements

The Bulk Shielding Reactor comprises little more than an assembly (*lattice*) of enriched uranium fuel elements immersed in water. The height of the active lattice is 24 inches, and for a typical loading the other dimensions might be  $15 \times 18$  inches. The reactor supplies a thermal neutron flux of about  $10^{12}$  neutrons/cm<sup>2</sup>-sec when operated at 100 kilowatts heat output, and about  $10^{13}$  neutrons/cm<sup>2</sup>-sec at a power level of 1000 kilowatts. Figure 3-6 shows the reactor core in operation. The glow (known as *Cerenkov radiation*) is produced by beta particles moving in water with velocities exceeding the velocity of light in water.

## BASIC TYPES OF NUCLEAR REACTORS

**INSTRUMENT BRIDGE**

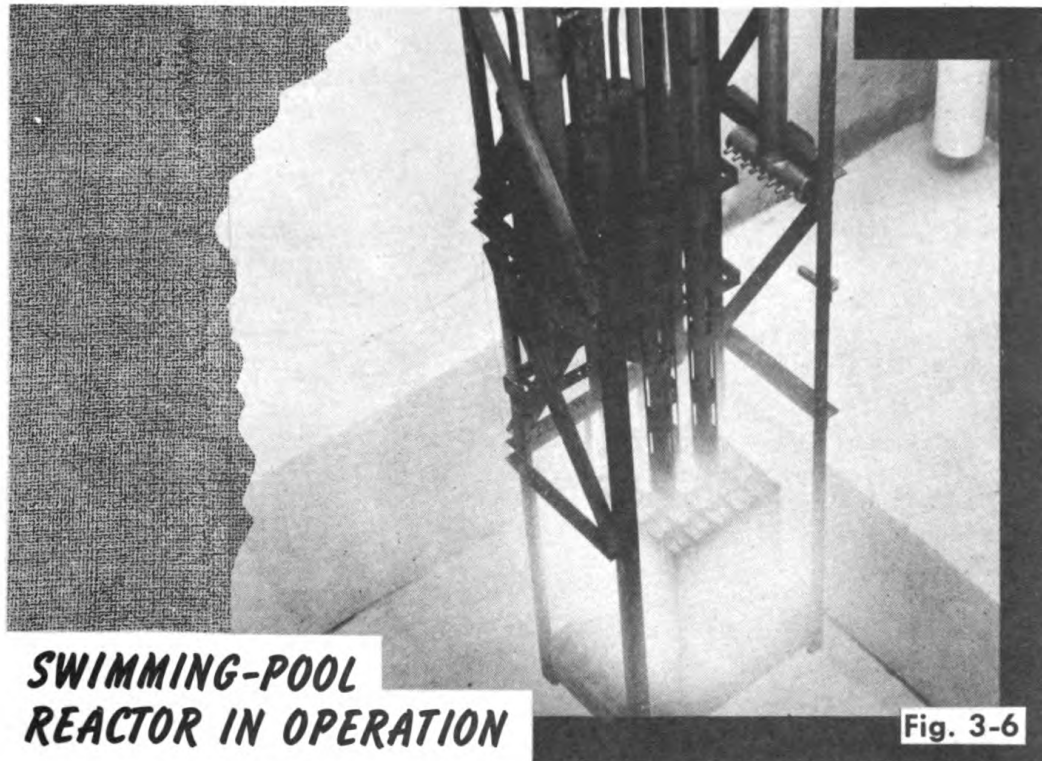
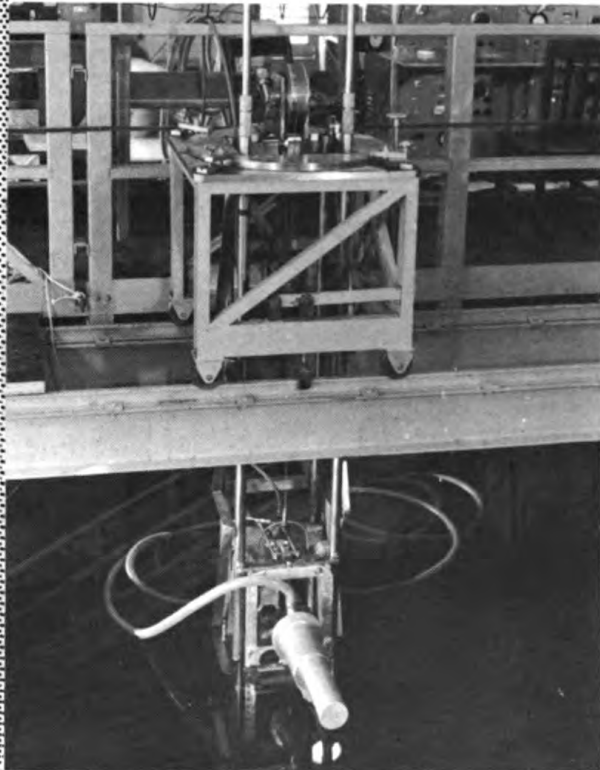
**AND FRAMEWORK**

**from which**

**instruments are**

**lowered into the pool**

**Fig. 3-5**



**Fig. 3-6**

## NUCLEAR ENERGY AND POWER REACTORS

The fuel elements are hollow bundles of plates through which water flows by natural convection, acting as both moderator and coolant. (The pool water also serves as reflector and shield.) There are two types of fuel elements, standard elements and special elements, for the insertion of control rods. The standard element is about  $3 \times 3$  inches in cross section and 35 inches long, including a conical end section (refer to Fig. 3-6). The *active* (fuel) section is 24 inches long and has the shape of a rectangular pipe. Inside each pipe are 18 curved fuel plates, consisting of a highly enriched uranium-alloy sandwiched between aluminum sheets. The fuel "sandwiches" are separated by a cooling channel  $\frac{1}{8}$  inch wide and require about 140 grams U-235 "meat" for a standard fuel element (18 plates). The control-rod receiving fuel elements are similar to the standard element, except that

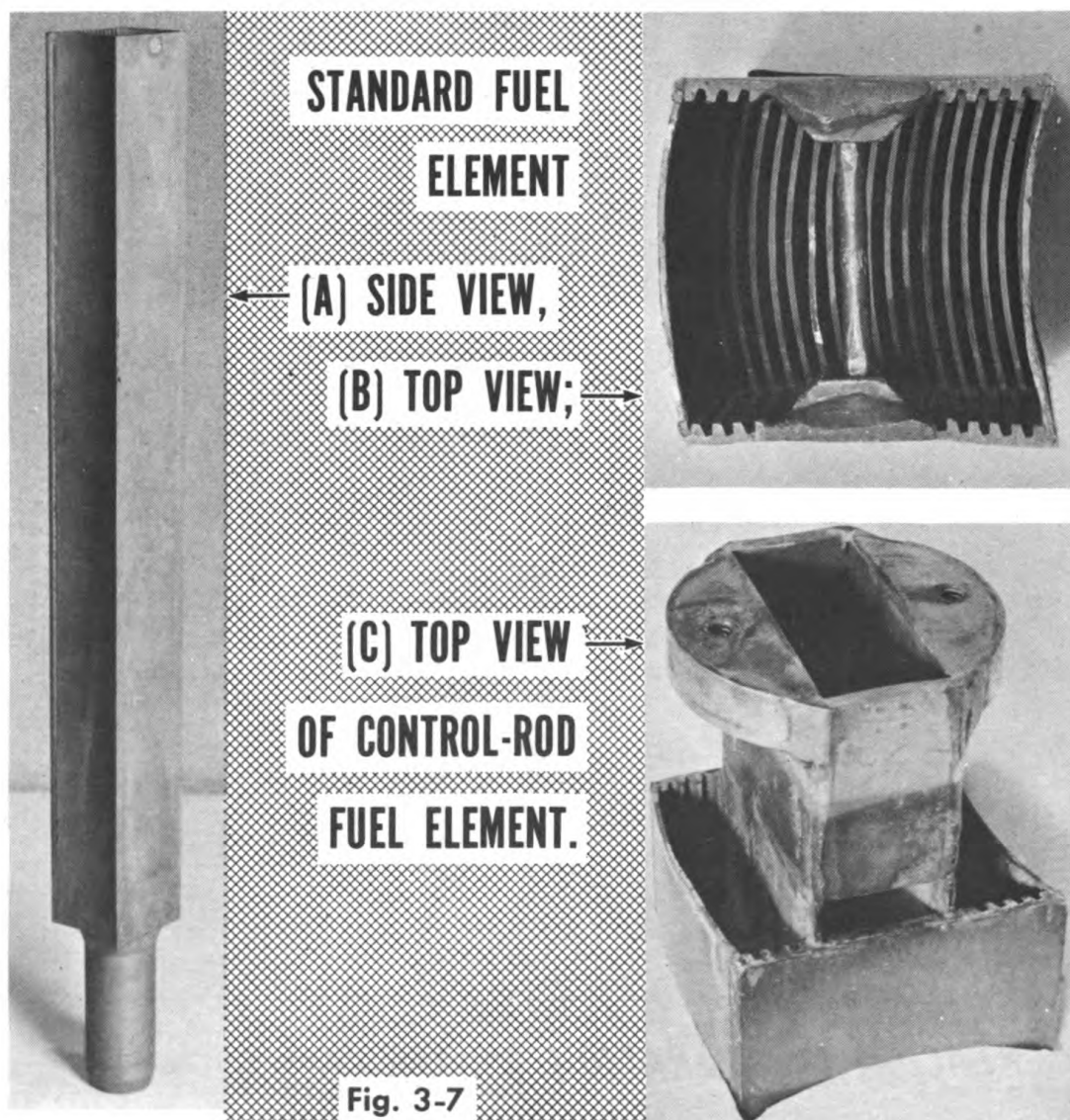
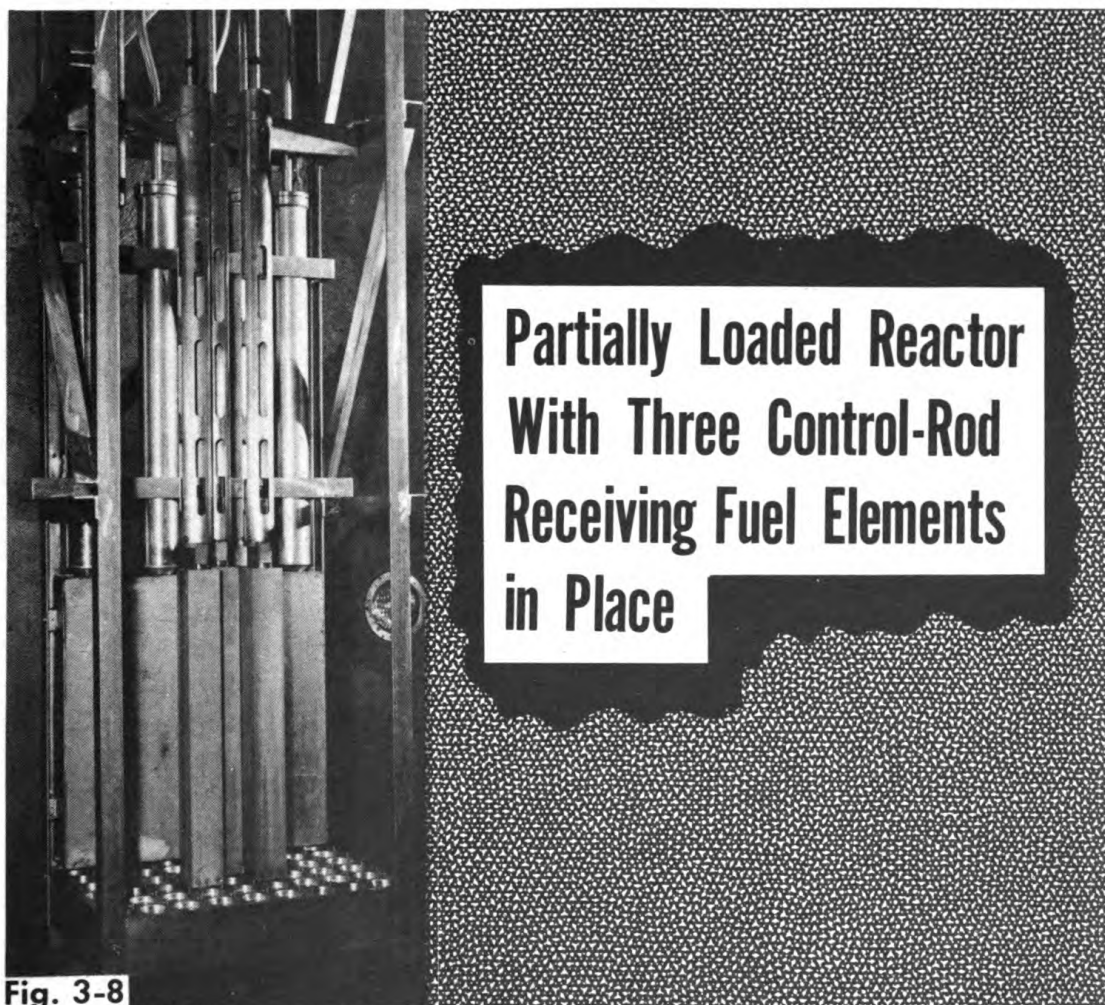


Fig. 3-7

## BASIC TYPES OF NUCLEAR REACTORS

about half the fuel plates have been removed to provide a slot for the entry of the control rod. The rods move readily in and out of the slotted elements. (See Fig. 3-7.)

The fuel elements rest on a supporting 54-hole grid plate, which permits various loading arrangements within the  $6 \times 9$  unit pattern. A typical loading requires 30 fuel elements with a total weight of about 4 kilograms (approximately 9 lbs) of enriched uranium. Fuel is consumed at the rate of 1 gram per *megawatt day* (1 million watts for 24 hours). The fuel elements must be reprocessed when 5 to 10 percent of the fuel has been consumed, permitting operation for about 1 megawatt year. Figure 3-8 shows the



reactor partially loaded with three control-rod-type fuel elements in place. Note the aluminum grid structure at the bottom. The cans above the fuel elements contain the electromagnets that support the control rods. The cylindrical aluminum cans behind them contain ionization chambers. For experiments with various neutron reflectors, the front row of the reactor

## NUCLEAR ENERGY AND POWER REACTORS

grid plate is frequently filled with dummy elements, containing graphite, beryllium oxide (BeO), or some other material.

### Control and Safety System

The reactor is controlled by means of two boron-carbide *shim safety rods* for coarse reactivity control and one automatic (servo) control rod for fine regulation. An iron armature at the top of each rod is suspended from an electro-magnet, which can be raised or lowered by a small electric motor. The magnets release the rods to fall by gravity if the power is cut off, if the neutron or gamma flux becomes excessive, or if other major trouble develops. Interlocks prevent raising the safety rods unless the control rod is inserted all the way, and the control rod, in turn, cannot be operated until the safety rods are at least three-fourths withdrawn.

The BSR and other pool reactors are inherently safe for moderate excess reactivities ( $k$  within 2% of unity), because they have a *negative temperature coefficient*. This means that a slow rise in reactor power, which causes the water to heat up, *decreases the reactivity* bringing the system back into balance. Even if the power is increased suddenly by deliberately pulling out all control rods, the boiling water between the fuel plates will carry away portions of the moderator, thus stopping the chain reaction. Moreover, the fission products formed in the fuel elements are contained within the fuel plates and do not contaminate the water.

A variety of instruments are provided for reactor control and safety. These include *differential ionization chambers*, *boron-coated ionization chambers*, a *fission chamber*, and a *gamma chamber*, all essentially similar to the types discussed in connection with the graphite-moderated reactor. A monitron, equipped with a boron-coated chamber, surveys the amount of radioactivity in the general area and is interconnected with a safety alarm circuit. Many of these measuring instruments must operate under water and, accordingly, are enclosed in watertight aluminum or polystyrene cases filled with compressed gas. Figure 3-9 shows an underwater ionization chamber with associated preamplifier. The controls for the reactor and the various indicating and recording instruments are brought together in a central control room.

### Costs

A pool-type reactor is one of the least expensive reactors to build and operate. The construction costs for the entire Bulk Shielding Reactor (in 1950) were about \$247,500, out of which amount approximately \$153,000 was spent for the reactor building and pool, the remainder going for reactor essentials and other equipment. This figure does not include, however, the cost of the enriched uranium fuel and later relocation of the control panels.

### Heavy-Water-Moderated Reactors

It was recognized even in the early days of reactor design that heavy water is a better moderator than graphite or light water, because it is more

## BASIC TYPES OF NUCLEAR REACTORS

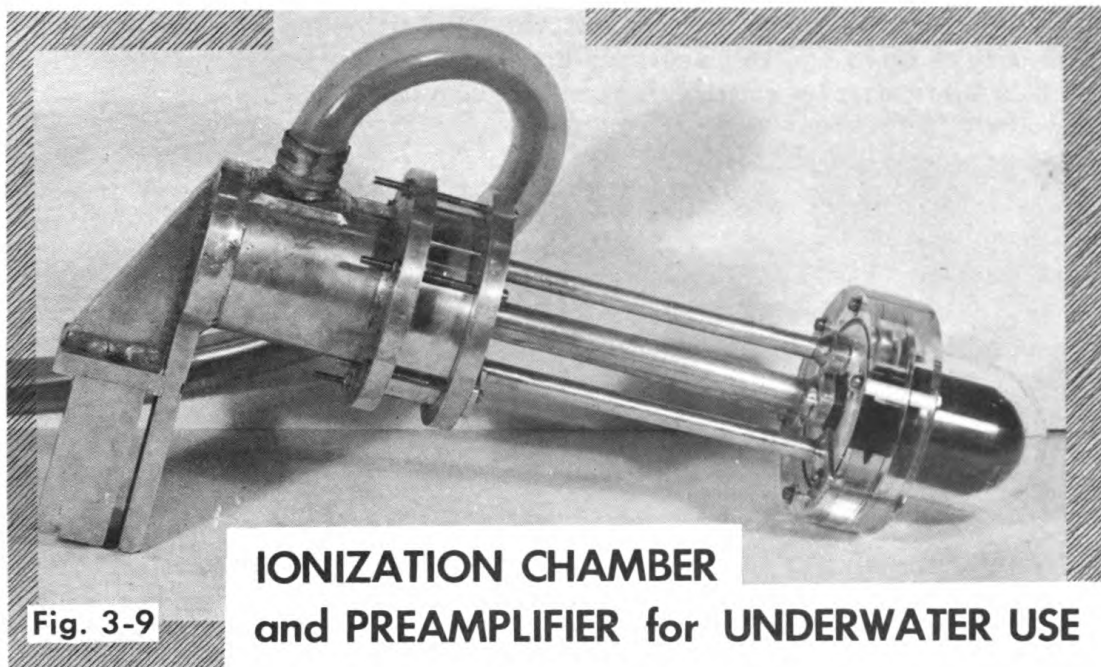


Fig. 3-9

### IONIZATION CHAMBER and PREAMPLIFIER for UNDERWATER USE

effective in slowing down neutrons and is less prone to withdraw them from the chain reaction by absorption. Accordingly, a reactor moderated with heavy water has a higher multiplication factor, smaller size and critical mass, and greater thermal-neutron flux than a comparable light-water or graphite moderated reactor. Moreover, the neutron flux is relatively uniform over a large volume of the reactor core, providing a large experimental work area at high neutron-flux levels. The cost of this type of reactor is intermediate between light-water and graphite-moderated types of comparable power.

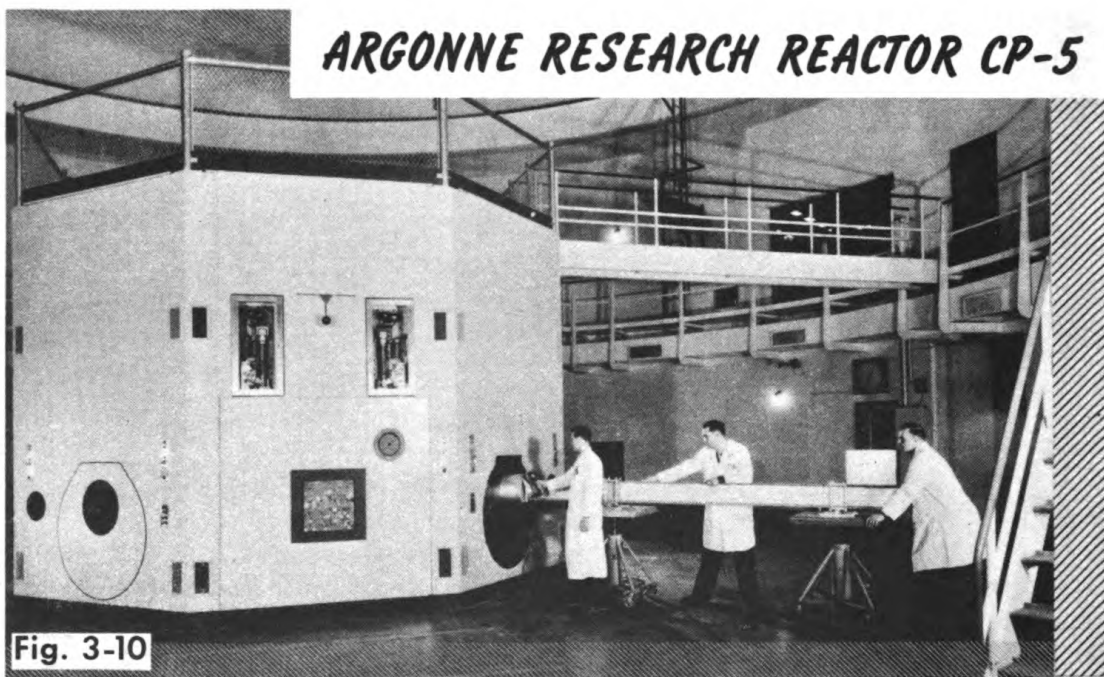
The prototype of the heavy-water reactors is the Argonne heavy-water reactor CP-3, which went into operation at the Argonne National Laboratory in May 1944. (The designation, CP-3, stands for "Chicago Pile No. 3", the third of a series starting with the historic first reactor, the CP-1.) The CP-3 was replaced by the more powerful CP-5 reactor, which has been operating at Argonne since February 1954. Another heavy-water reactor is the NRX (National Research Experimental) reactor at Chalk River, Canada, which was designed jointly by Canadian, British, and U.S. scientists. Unfortunately, this large 10-megawatt reactor was damaged in late 1952. The most modern reactor of this type is the 1000-kilowatt Massachusetts Institute of Technology Reactor, which recently went into operation.

#### Argonne Research Reactor (CP-5)

The Argonne CP-5 reactor (Fig. 3-10) is typical of heavy-water moderated reactors and is, perhaps, the most versatile and efficient research reactor in existence. Using highly enriched (90% U-235) uranium as fuel, and heavy

## NUCLEAR ENERGY AND POWER REACTORS

water as both moderator and coolant, the CP-5 provides a high neutron flux intensity of up to  $3 \times 10^{13}$  neutrons/cm<sup>2</sup>-sec at an average power (heat) level of 1000 kilowatts. Its critical mass is only about 1.7 kg of U-235.



The reactor is at the center of a circular room 70 feet in diameter, which is reserved entirely for research equipment and auxiliary shielding. The reactor operators have a view of the reactor and the surrounding experimental area from a control room on the second floor. A circular catwalk extending along the wall of the reactor room has three staircases leading to the main floor (reactor) area. (They are carefully placed to avoid neutron beam areas.) The top of the reactor is reached by a bridge that can be shifted between two places along the catwalk. The reactor itself has the shape of an octagon, approximately 13 feet high and 20 feet in diameter. (See Fig. 3-11.) More than 50 openings on its eight sides and the top permit simultaneous operation of many research projects, such as sample irradiation, neutron beam work and radioisotope production.

### Reactor and Shield

The core of the reactor is at the center of a 6-foot diameter aluminum tank. Heavy water (D<sub>2</sub>O) acting as coolant, flows upward by forced convection through box-type fuel assemblies and then discharges into the tank. A pipe at the bottom of the tank conducts the heavy water into a light-water heat exchanger, which receives the heat generated by the reactor, and then returns the heavy water to the tank.

## BASIC TYPES OF NUCLEAR REACTORS

HEAVY-WATER-MODERATED SYSTEMS

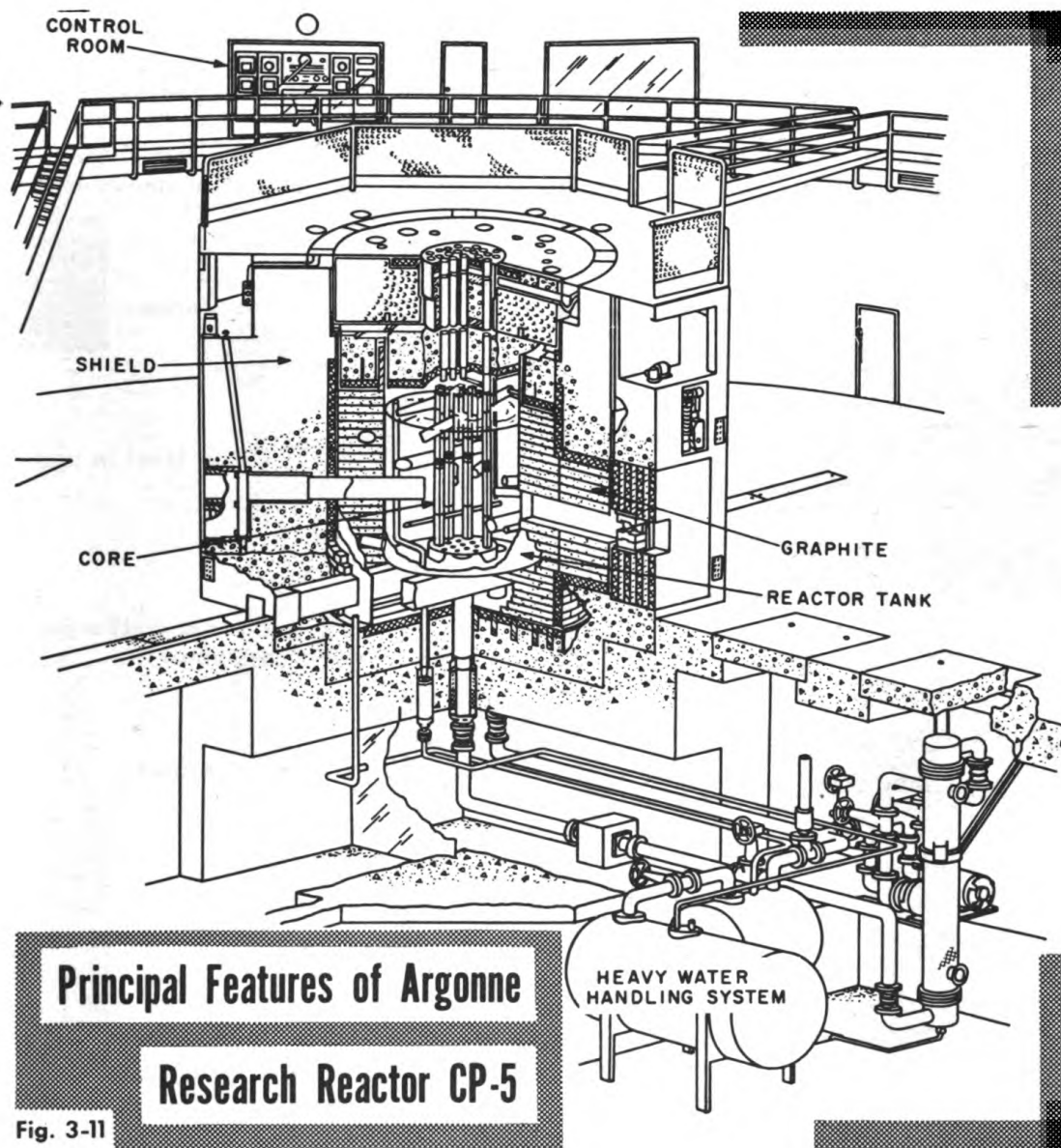


Fig. 3-11

The region of heavy water above the reactor core is occupied by four control rods, moving in and out of the core between the parallel rows of fuel assemblies. A region 2 feet thick around and below the core is available for experimental work. A secondary neutron reflector, in addition to the heavy water, is provided in the form of a 2-foot thick graphite zone extending around and below the tank. Outside the graphite, the neutrons and gamma rays are absorbed in a massive shield, consisting (from the inside out) of a boron-carbide liner, a  $3\frac{1}{3}$ -inch-thick lead shield, and finally a limonite/iron-ore-aggregate/concrete shield. The total thickness of the shield is about 5 feet.

## NUCLEAR ENERGY AND POWER REACTORS

### Fuel Assembly and Loading

A number of box-type fuel assemblies (about 12 for a critical mass) are provided, each containing 10 curved aluminum/uranium/aluminum-sandwich fuel plates similar to those of the BSR light-water reactor. There are five parallel rows of these assemblies. As shown in Fig. 3-12, the heavy-water

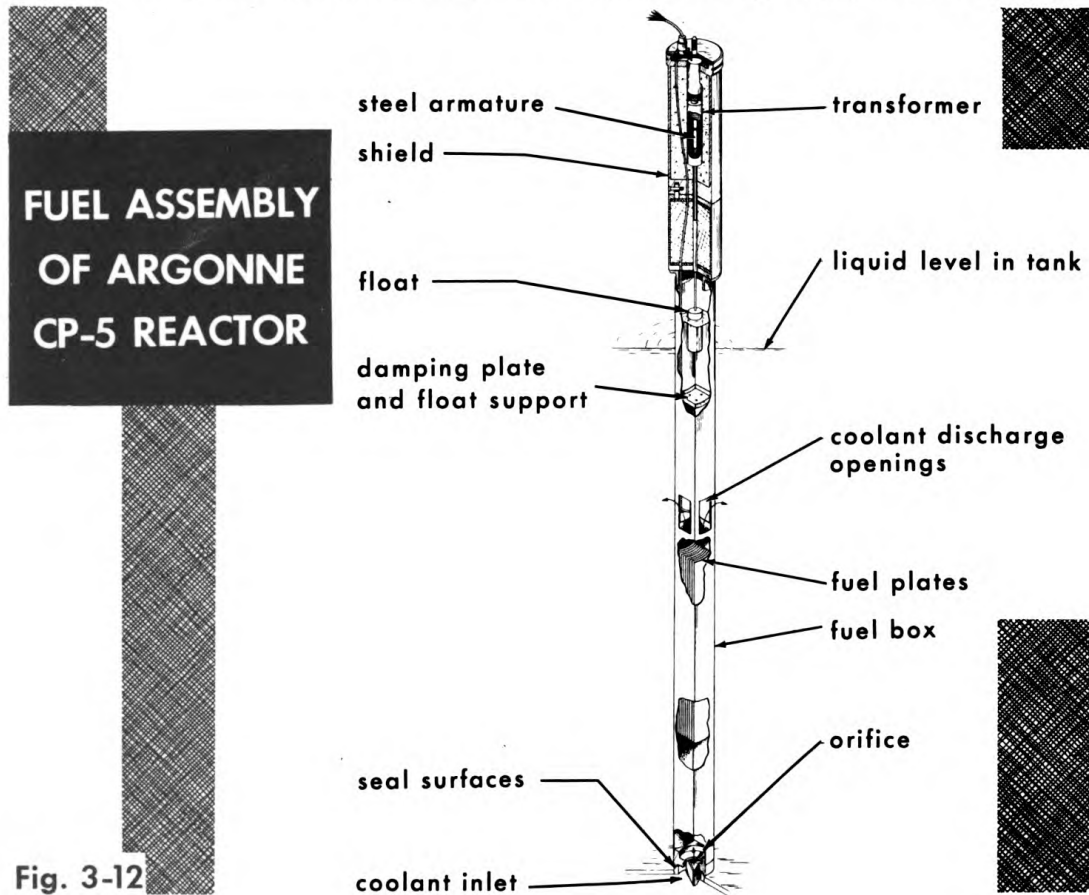


Fig. 3-12

coolant enters through an inlet opening in the seal, cools the active plates, and then discharges through ports into the tank. The hydraulic force of the upward flow causes the water level in the fuel assemblies to be several inches higher than the level in the tank. This added height is measured by a float with a stainless-steel mast, which enters through the core of a transformer near the top of the element. The transformer gives an indication of liquid flow rate through the element.

When about 20 percent of the original U-235 in a fuel assembly is converted into fission products, refueling becomes necessary. Fuel loading and unload-

## BASIC TYPES OF NUCLEAR REACTORS

ing is accomplished through individual openings passing through the top shield and aligned with each of the fuel channels. For a 1000-kw power level, refueling must be performed at about eight-months intervals.

### Reactor Control, Instrumentation and Safety

The reactivity of the reactor is controlled by four *shim-safety-control rods* and a fifth *regulating rod* for fine control. The four shim safety rods (Fig. 3-13) are strong neutron-absorbing units, which move inside the reactor

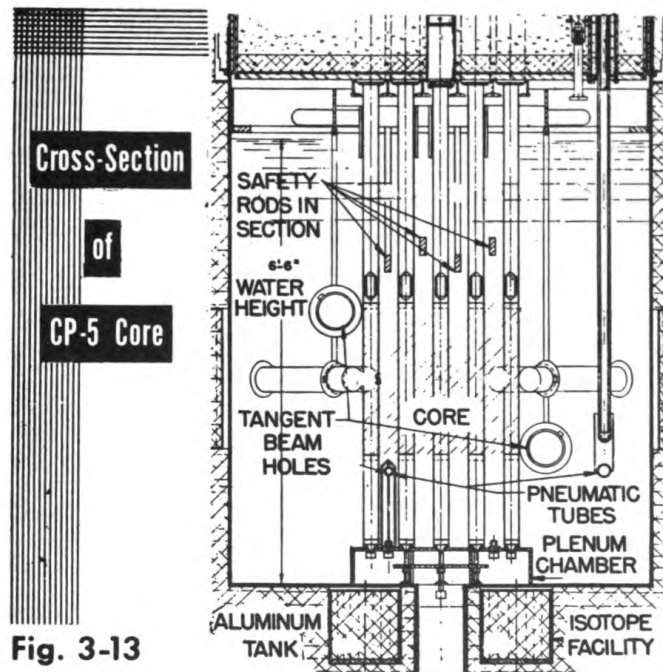


Fig. 3-13

core between the parallel rows of fuel assemblies. The purpose of these rods is to adjust for gross changes in reactivity, and also to shut the reactor down quickly upon receipt of a "scram" or shutdown signal. Any two of the safety rods are sufficient to override temporary excess reactivity.

The fine control or regulating rod moves up and down for a short distance outside the fuel-assembly array. Its functions are to make the reactor critical, to keep the reactivity equal to unity, and to adjust or alter the power level. Since it determines the behavior of the reactor, the regulating rod moves faster than the shim-safety rods. A servo follow-up drive system above the reactor permits maintaining a steady power level by automatic control.

Small changes in reactivity to compensate for shutdown periods are attained by a *chilled-water system*, based upon the fact that a *cold moderator adds reactivity*. Conversely, the *negative temperature coefficient* of the reactor returns the power level to balance during increases in reactivity. Even a drastic, sudden increase in reactivity or alteration in the chain reaction simply results in the boiling away of the heavy-water moderator and auto-

## NUCLEAR ENERGY AND POWER REACTORS

matic shutdown. As an added safety feature, the heavy water in the aluminum tank may be rapidly drained to the level of the fuel plates by a quick-opening valve and limited-capacity storage tank.

The instruments that indicate and record the power level of the chain reaction from start-up to full power are similar to the neutron-flux measuring instruments previously described. The sensing instruments that follow the chain reaction behavior are various types of ionization chambers, each selected for maximum efficiency in a particular power range. The indicating instruments that make the electric signal from the ion chambers visible are *vibrating-reed electrometers* for the feeble signals during reactor start-up and a variety of galvanometers for indicating higher power levels.

The operator in the control room acts upon the indicated reactivity information either by closing circuits to the drive motors of the control rods or by deenergizing the magnetic clutches to drop the rods, if shutdown is desired. A dial indicates the position of each shim-safety rod; a register, that of the regulating rod.

The cost of the CP-5 reactor, excluding 7 tons of heavy water, is \$1,051,000; the cost of the shield is \$403,000. The total for the entire facility comes to \$2,250,000.

### Homogeneous Enriched-Fuel Reactors

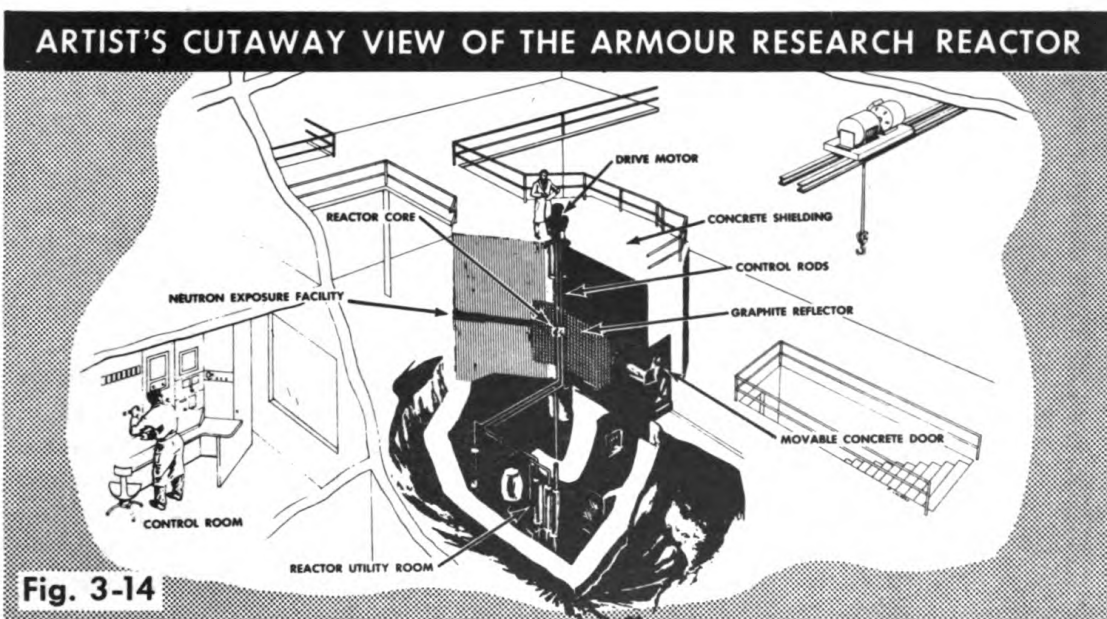
The first research reactors with enriched uranium utilized it in the form of a (light) water solution of uranyl sulfate or uranyl nitrate as moderator-fuel. Because the uranium fuel is evenly dispersed in the water solution (acting as moderator), these reactors are known as *homogeneous* solution type reactors. They are also frequently called *water boilers* because there is a slow bubbling of hydrogen and oxygen caused by the decomposition of water during operation. Boiling does not occur, however, since the solution is normally kept below 80°C by a circulating water coolant. (The homogeneous water boiler is *not* the same as the heterogeneous *boiling-water reactor*, to be discussed in the next chapter.)

Theoretically it is possible that a homogeneous reactor could use a *solid* moderator-fuel combination and at least one such reactor, using a polyethylene-uranium oxide mixture, has actually been built. This offers no particular advantage, however, since it involves the same expensive, careful machining and canning of the uranium that is required in heterogeneous reactors.

In the solution-type reactor about 14 liters (3.7 gallons) of the moderator-fuel solution are contained in a spherical, corrosion-resistant tank of 1 foot diameter. This small reactor core is surrounded by a graphite layer about 2 feet thick, serving as neutron reflector. The reflector is generally elongated in one direction to provide a column of thermal neutrons (*thermal column*). From 2 to 5 feet of concrete, depending on the power level, serve as shield around the graphite reflector.

## BASIC TYPES OF NUCLEAR REACTORS

A critical mass, typically less than 1 kilogram of U-235, is maintained by adjusting the uranium concentration of the solution through a "mixing bowl" arrangement. (See Fig. 3-14.) The neutron flux may be as high as  $2 \times 10^{12}$  neutrons/cm<sup>2</sup>-sec for a 50-kilowatt unit operating at full power. The flux for a 1-watt reactor, however, is only about  $4 \times 10^7$  neutrons/cm<sup>2</sup>-sec. As the power is increased beyond about 30 kw, the highly energetic fission fragments rapidly decompose the water in the core into elemental oxygen and hydrogen and the uranium solution tends to become unstable. This makes it necessary at high power levels to use a *gas recombination system* to recombine hydrogen and oxygen into water and return it to the core. Since radioactive gases are evolved in the process, the gas system must be completely enclosed and placed in a shielded area.



The small size of the reactor core limits the area available for control and experimental purposes. The safety and regulating (control) rods generally extend through the graphite reflector to the surface of the reactor tank. The major experimental facility is a hole, called the "glory hole," passing through the tank at the center of the core. Other experimental openings, such as thermal columns, beam tubes, isotope-production tubes, etc., are arranged about the core with suitable openings through the shield and reflector, according to their purpose.

A desirable safety factor of homogeneous reactors is their negative temperature coefficient. Another advantage is that excessive fuel need not be initially loaded into the reactor and that the uranium enrichment may be as low as 15 to 20% (The reactors we shall describe, however, have an enrichment as high as 90% U-235.) These factors combine to make the homogeneous-type reactors compact, safe and relatively inexpensive. They are used primarily

## NUCLEAR ENERGY AND POWER REACTORS

in education, research, and other applications not requiring the highest thermal-neutron flux intensities.

### Development

The first "water boiler" reactor was built by the Los Alamos Scientific Laboratory and placed into operation in 1944. The unit was appropriately called LOPO (Low Power), because it operated at a power of only about 0.05 watt. LOPO was later converted to operate at successively higher powers: the HYPO unit at 6 kilowatts, and the SUPO (Super Power) unit at 45 kw. An additional reactor of this type, operating at 10 kw, was placed into operation in 1953 at North Carolina State College. Two examples of homogeneous reactors described in the following pages are the *Livermore* (L-3) reactor, operating at the University of California since 1953, and the 50-kilowatt *Armour Research Reactor*, operating since 1956 at the Armour Research Foundation, in Chicago, Ill.

### Livermore Research Reactor (L-3)

The 500-watt Livermore "water boiler" (already shown in Fig. 3-14) consists of a spherical-core tank slightly more than a foot in diameter, which contains 4 gallons of uranyl sulfate solution. The sphere is imbedded in the center of a circular cylinder of graphite, 5 ft in diameter and 5 ft high. The graphite reflector, in turn, is contained in a steel tank which is lined with a 5-inch-thick layer of lead to provide protective shielding. When the reactor is operated at full 500-watt power, the thermal neutron flux at the center of the spherical core is about  $2.4 \times 10^{10}$  neutrons/cm<sup>2</sup>-sec. A 1.1-inch diameter "glory hole" passes completely through the reactor at the core center and terminates at the outer edge of the shield, allowing access to the high-flux regions in the center. The experimental facilities are further complemented by eight removable *stringers* on the south side of the reactor, which extend through the core and shield on both sides of the sphere. The stringers are 3-foot long graphite and lead bars, whose removal permits access to the core for inserting experimental materials.

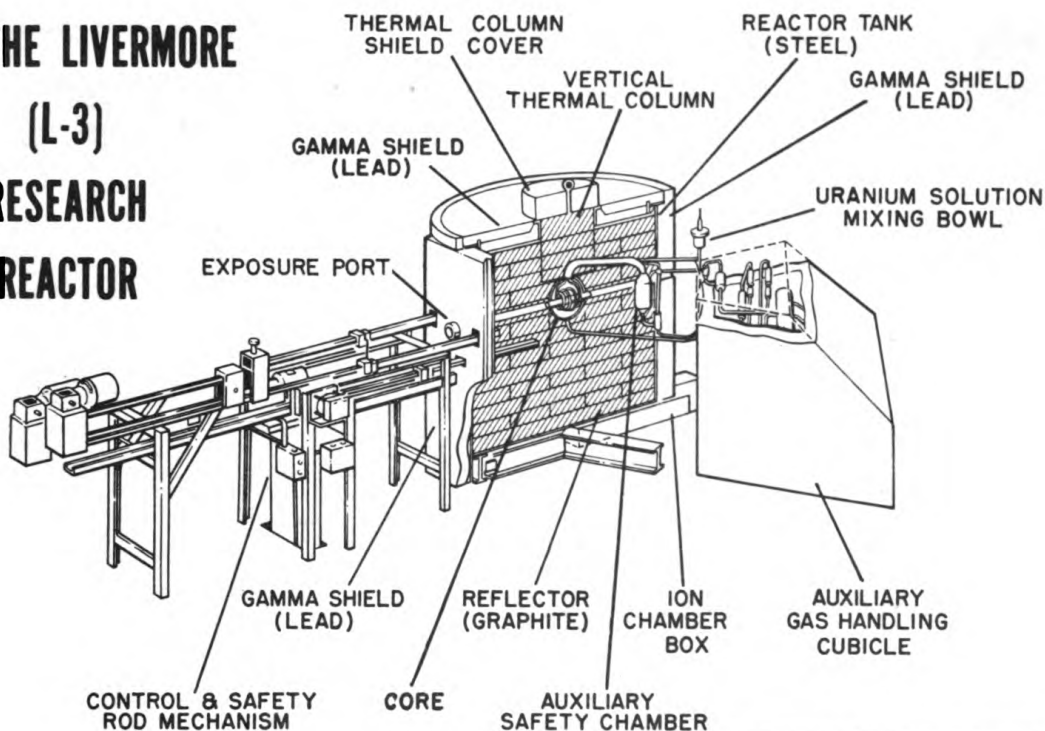
Two safety rods and two control rods, shown at left of Fig. 3-15 permit reactivity control of the reactor. The two boron-carbide safety rods are operated by electric drive motors that accomplish complete withdrawal within 7 seconds. Magnetically-actuated latches normally hold the rods, but quickly drop them into the reactor, if the latches are deenergized at any time by one of the alarm or "scram" circuits. The two control rods, which are similar in construction to the safety rods, consist of a *coarse-control* unit to bring the reactor up to power and a servo-operated *regulating rod* to maintain automatic power regulation.

### Armour Research Reactor

This 50-kilowatt "water boiler" consists of a stainless steel spherical reactor

## BASIC TYPES OF NUCLEAR REACTORS

### THE LIVERMORE (L-3) RESEARCH REACTOR



### A 500-WATT WATER BOILER

Fig. 3-15

core, located at the center of a cylindrical graphite-reflector tank. The 12½-inch (outside diameter) sphere is filled with 3.7 gallons (14 liters) of uranyl-sulfate solution, containing approximately two pounds of highly enriched (88%) U-235. At maximum power, the unit supplies a thermal-neutron flux of about  $1.7 \times 10^{12}$  n/cm<sup>2</sup>-sec. The entire reactor (Fig. 3-15) is enclosed in a 5-foot thick shield of dense concrete.

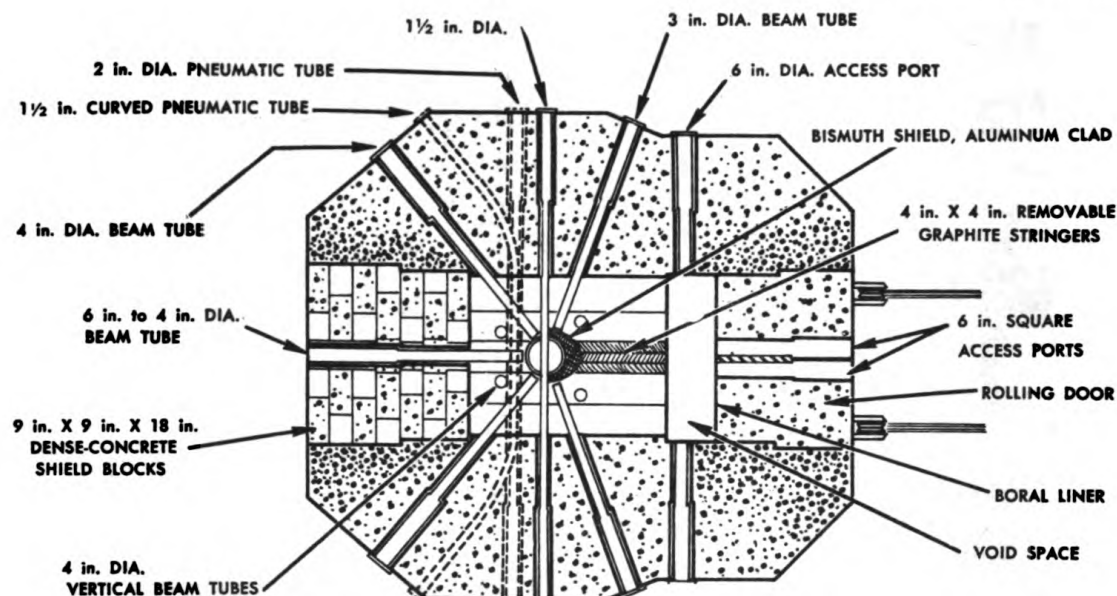
The high-powered Armour reactor is equipped with considerably more complex systems for fuel handling, gas-recombining, cooling and safety than the 500-watt Livermore reactor. (See Fig. 3-16.) Four control-rod thimbles and a fill-and-drain pipe pierce the upper half of the Armour reactor core. Various cooling coils, gas lines and liquid-return lines extend through the lower half of the sphere and into the gas-handling and heat exchanger equipment in the reactor utility room below. A 1½-inch "glory hole" enters the core obliquely from above.

A thin-walled, liquid-tight *outer enclosure envelope* is placed around the sphere and its piping to contain the uranyl sulfate solution in the event of a leak. An additional safety feature is a *spillover tank* incorporated into the gas-handling system. An uncontrolled power burst would result in rapid gas formation in the core solution that would force part of the solution into the spillover tank, causing the core to become subcritical.

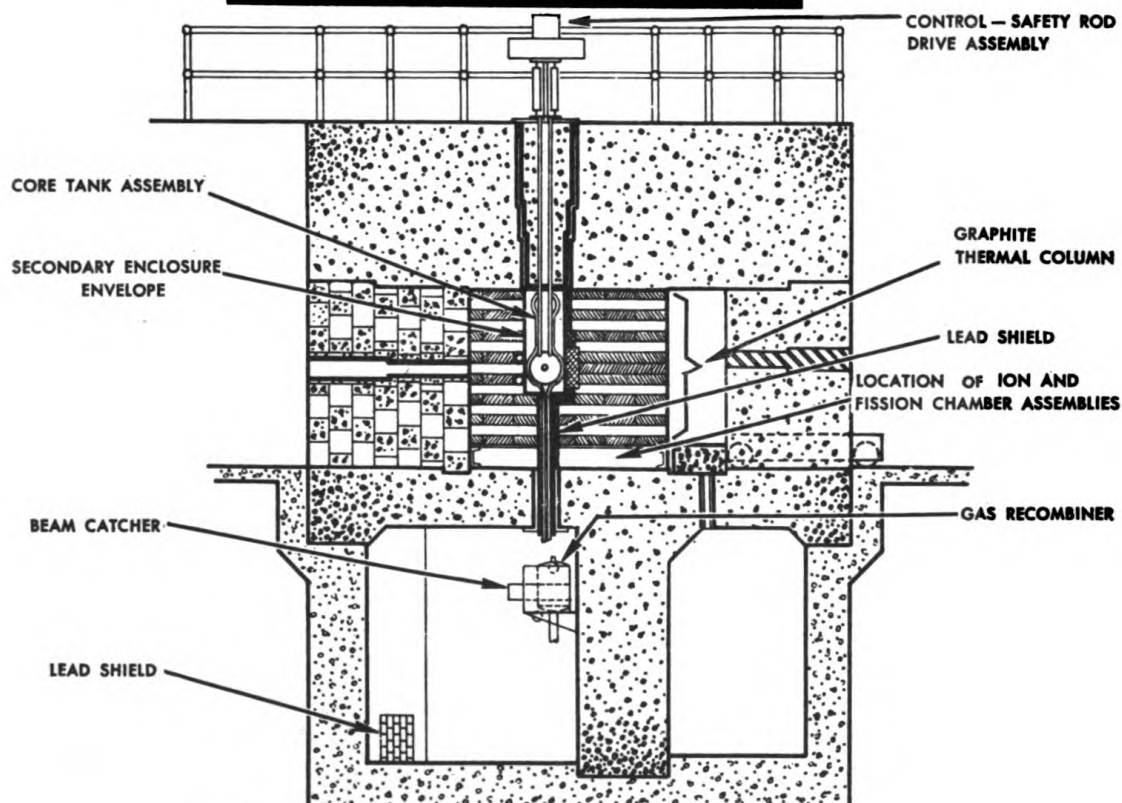
## NUCLEAR ENERGY AND POWER REACTORS

### ARMOUR RESEARCH REACTOR

EXPERIMENTAL BEAM TUBES AND GLORY HOLE EXTENDING THROUGH DENSE CONCRETE SHIELD TO REACTOR CORE.



### CORE TANK WITHIN A GRAPHITE BLOCK REFLECTOR



## BASIC TYPES OF NUCLEAR REACTORS

### Cooling System

The reactor core and gas-handling components are cooled by a closed recirculating refrigerator system using distilled light water. The core-cooling system consists of approximately 60 feet of stainless steel coils in the core (Fig. 3-17), associated pumps, valves and piping, and a water-to-freon heat



exchanger. Thermocouples indicate the temperature of the core coolant. The pump, instrumentation, and heat exchanger are located in the shielded reactor-utility room below the reactor.

### Gas-Handling System

The gas handling system has the primary functions of recombining the reactor-decomposed water and containing the fission product gases in a closed system. It must also provide for the periodic removal of the fission gases. The hydrogen and oxygen evolved from the water in the core are recombined by means of a *catalyst* (platinized alumina); a lift pump then

## NUCLEAR ENERGY AND POWER REACTORS

returns the condensate to the core. The entire system is designed to be gas-tight and explosion-proof.

### Control System

Four vertically-oriented *boron-carbide rods* provide regulation and shut-down for the reactor. These rods are located in thimbles that pierce the core tank and have a combined control capacity of 8% excess reactivity. Three of the rods are used for power regulation and all four function as shutdown rods. If the reactor is "scrammed" by some alarm condition, all four rods are automatically released and fall into the core by gravity. The positions of the rods are indicated on the control console by means of a *synchro follow-up system*.

The reactor power level is automatically maintained by feeding an "error" signal from a power level recorder to a servo amplifier, which then drives the regulating-rod motor in the direction required to correct the "error" (power deviation). The signal feeding the automatic control system can originate from either of two ion chambers or a fission counter tube. Provision is also made for *manual control* of the regulating rods.

The total cost of the Armour Research Reactor facility was about \$700,000, of which about 40 percent were expended on the reactor and shield.

## 4: POWER REACTORS AND PLANTS

With thorium and uranium the seventh and ninth most abundant elements in the earth's crust, their use as fuels in nuclear reactors would guarantee the world at least a 100-year supply of power. It is somewhat surprising, therefore, that no great rush has developed in this country to get nuclear power plants into operation, despite the general optimism a few years ago and the availability of nuclear designs and fuels. It is to be noted, however, that some foreign countries with a short supply of conventional fuels and the labor to dig them up, have made great strides in nuclear power development; this is particularly true for Great Britain.

The reasons for this apparent U.S. lag to get into the nuclear power field are inextricably bound up with knotty problems in the domains of economics, public policy and technical "know-how", in that order.

The key to nuclear power economics is the cost of nuclear fuels (thorium or uranium), with the cost of the power plant being a secondary, though important factor. The type and quantity of fuel depends, of course, on the reactor design. For reactors fueled with enriched uranium, the cost of the fuel typically runs to about *two-thirds* of the total cost per kilowatt-hour, while the capital investment and operating costs account for the remaining third. It is hoped that this ratio will become more favorable by getting more "mileage" from the fuel (in breeder reactors, for example), by lowering the initial cost of fuel processing, and perhaps by government commitments to buy back the plutonium produced in reactors. At present, however, the power cost of the only U.S. commercial nuclear power station, at Shippingport, Pa., is about 65 mils per kilowatt-hour (1 mil = 0.1 cent), as compared with a national average for conventional power stations of 7 to 8 mils. An experimental boiling water reactor (EBWR) at the Argonne National Laboratory, on the other hand, has been able to generate electrical power at about 32 mils per kilowatt-hour, the lowest thus far.

The public policy problems are essentially a new version of the old private vs public power controversy. At present, most American nuclear power projects are subsidized to some extent by the government. These subsidies range from an interest charge on government-owned fuel to heavily subsidized government-industry partnerships, and almost complete government ownership with respect to liability insurance.

Problems of technical know-how are in the process of being solved. Whole new technologies have been created to produce and use heretofore little-known materials. Materials of high neutron capture ability (called *capture cross section*), such as boron, cadmium and hafnium have been developed for use in control rods, while materials with a low neutron capture cross section have been produced for use in reactor tanks. The metal *zirconium* is now greatly preferred to stainless steel for reactor tanks because its low capture cross section (one-tenth of that of steel) assures that the reactor walls will not absorb a sufficient number of neutrons to extinguish the nuclear fire. Despite these advances, some basic metallurgical problems remain unsolved.

## NUCLEAR ENERGY AND POWER REACTORS

### Basic Power-Reactor Factors

A *conventional* power plant burns coal, oil, or gas to heat a boiler that produces high-pressure steam. The steam, in turn spins a turbine which has an electric generator coupled to it. The electrical output from the generator is then transformed to a very high voltage and fed to various distribution points over long power lines. In a *nuclear* power plant the coal hopper (or other fuel container) and steam boiler are replaced by a nuclear reactor and a different kind of steam boiler, known as a *heat exchanger*. The heat exchanger utilizes the reactor-produced heat, carried in by a coolant, to boil a usually separate water supply. The boiling water then produces steam, which turns the turbo-generator and generates electricity, in the same way as in the conventional plant (Fig. 4-1). Thus, the nuclear reactor and heat

*A conventional power plant burns coal to produce steam, which spins a turbine generator, generating electricity.*

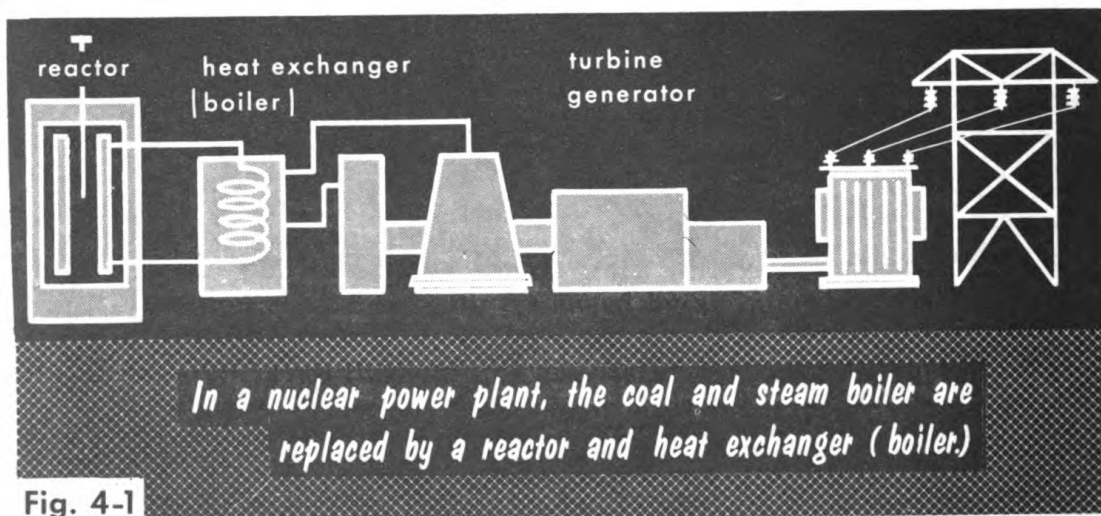
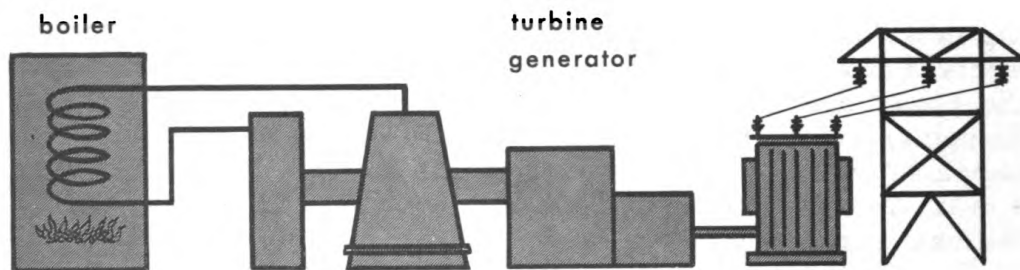


Fig. 4-1

## POWER REACTORS AND PLANTS

exchanger replaces *only a part* of the steam-generating plant and does not affect at all the electrical generating and distribution system.

### Choice of Reactor

The first power reactors were used for the propulsion of submarines. The *pressurized water reactors* (PWR) used for this purpose are safe, but fairly expensive and none too efficient. Based on the backlog of experience gained with the PWR submarine reactors, essentially the same design was chosen for the first commercial power reactor, at Shippingport, Pa. What is practical for specialized military uses has proven itself too uneconomical to compete with the more conventional ways of producing electrical power. The high power cost of the PWR reactor makes it unlikely that many more of this type will be built for commercial power production, except for foreign countries that lack power and conventional fuels.

The obsolescent PWR type is in the process of being replaced by more promising reactors, such as the *boiling-water reactors*, *sodium-cooled types*, *breeder reactors*, *homogeneous reactors*, and various experimental types. We shall study some of these in this chapter.

### Choice of Heat Exchanger

The hotter the steam, the more power can be gotten from it. The heat and pressure of the steam, in turn, depend on the temperatures attained within the reactor, the coolant that carries the heat produced by fission to the heat exchanger, and on the efficiency of the heat exchanger itself. We shall become acquainted in the following pages with the main types of reactor coolants (water under pressure, gas, and liquid metals) and various heat exchangers.

### Materials of Construction

We have already mentioned the problem of obtaining materials for reactor construction that can withstand intense nuclear irradiation for long periods. Among stable substances used at the present time are beryllium, graphite, and zirconium. These materials are undergoing extensive tests in experimental reactors, especially with respect to their corrosion resistance to liquid-metal and other unconventional coolants.

### Site Selection and Chemical Processing

The choice of plant location is intimately bound up with problems of radioactive waste disposal and decontamination. Nuclear reactors generate large quantities of radioactive fission products, which must be properly disposed of if they are not to contaminate the air or drinking water and cause biological damage. Commercial nuclear power stations cannot be located on the extensive government reservations, which are used to take care of storage and waste disposal problems for government reactors. Thus,

## NUCLEAR ENERGY AND POWER REACTORS

careful consideration must be given to the design and availability of a suitable waste disposal system, when selecting a site. Among the disposal methods used are storage in underground tanks; dilution, either by the atmosphere, in liquids, or in solids; sea disposal (in sealed containers); or burial, either under the site or at a national burial ground.

The irradiated fuels of the reactor must be chemically processed not only to remove, and decontaminate, and store the radioactive wastes, but also to recover valuable fissionable material, such as plutonium or U-233, and to isolate useful radioactive isotopes. Although the production of radioactive isotopes is not a primary function of power reactors, the recovery of plutonium and other fissionable fuels represents an important source of income, especially since the government appears willing to buy them back at attractive prices.

### Types of Power Reactors

In the last chapter we became acquainted with the basic types of reactors developed for research purposes. Let us now look at some power-reactor offshoots of these early designs. First we shall describe the popular *pressurized-water* and *boiling-water* reactors, which are both light-water-moderated tank types. Then we shall go on to *sodium-cooled, graphite-moderated* reactors, which have but little resemblance to the graphite-moderated natural uranium (BNL) reactor we described in the last chapter. Next we shall look into some experimental homogeneous (fluid-fuel) reactors, both of the light-and heavy-water-moderated types. We shall also become acquainted with the promising *breeder reactors*, which are fast reactors without any moderator. Finally we shall attempt to guess what the future might have in store in the form of *organic moderated, liquid-metal-fueled, gas-cooled* and other types of experimental reactors.

### Pressurized-Water Reactor (PWR)

The first full-scale commercial nuclear power plant is the 60,000-kw pressurized-water reactor at Shippingport, Pa., which we shall discuss in detail. An even larger reactor of this type, designed to produce 275,000 kilowatts for the New York area, is being built by the Consolidated Edison Company of New York and is to "go critical" in 1960. Others are being planned and built.

A pressurized water reactor (PWR) is a light-water moderated tank reactor that uses uranium fuel, usually in the form of a highly U-235 enriched "seed" surrounded by a "blanket" of natural uranium. A constant stream of ordinary water under high pressure flows through the core of the reactor and is heated by it to a temperature of about 550° F. An operating pressure of about 2000 pounds per square inch (psi) prevents the water from boiling at these high temperatures. The water, which also serves as moderator, flows through the heat exchanger and back to the reactor in

## POWER REACTORS AND PLANTS

a closed system of pipes to prevent the escape of radioactive fission products. In the heat exchanger, the heat of the pressurized water is transferred to a separate supply of low-pressure water, which is converted into low-pressure steam (about 600 psi). This steam, in turn, spins the turbine that turns the electric generator. The entire plant, except the turbogenerator, is usually steel-enclosed, safeguarding against radioactivity in case of a leak.

### PRINCIPLE OF PRESSURIZED WATER REACTOR

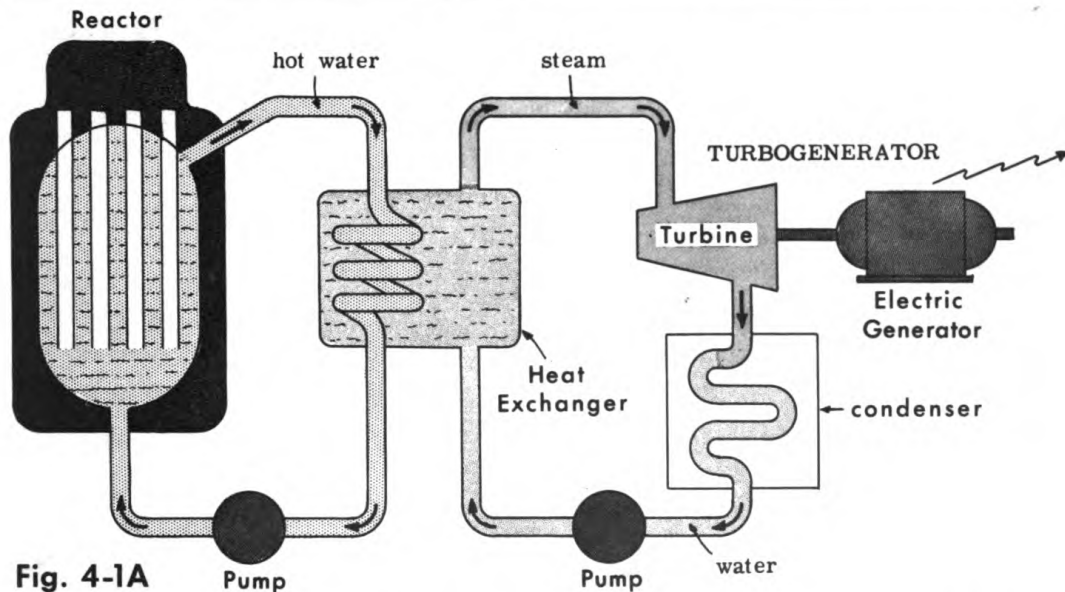


Fig. 4-1A

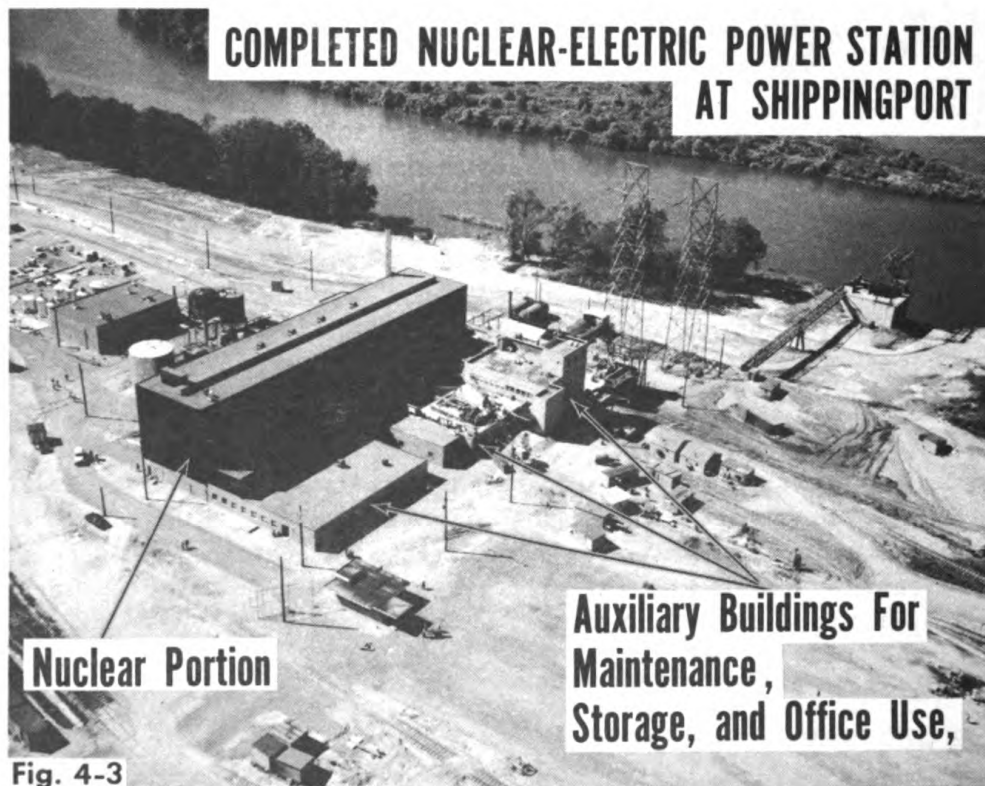
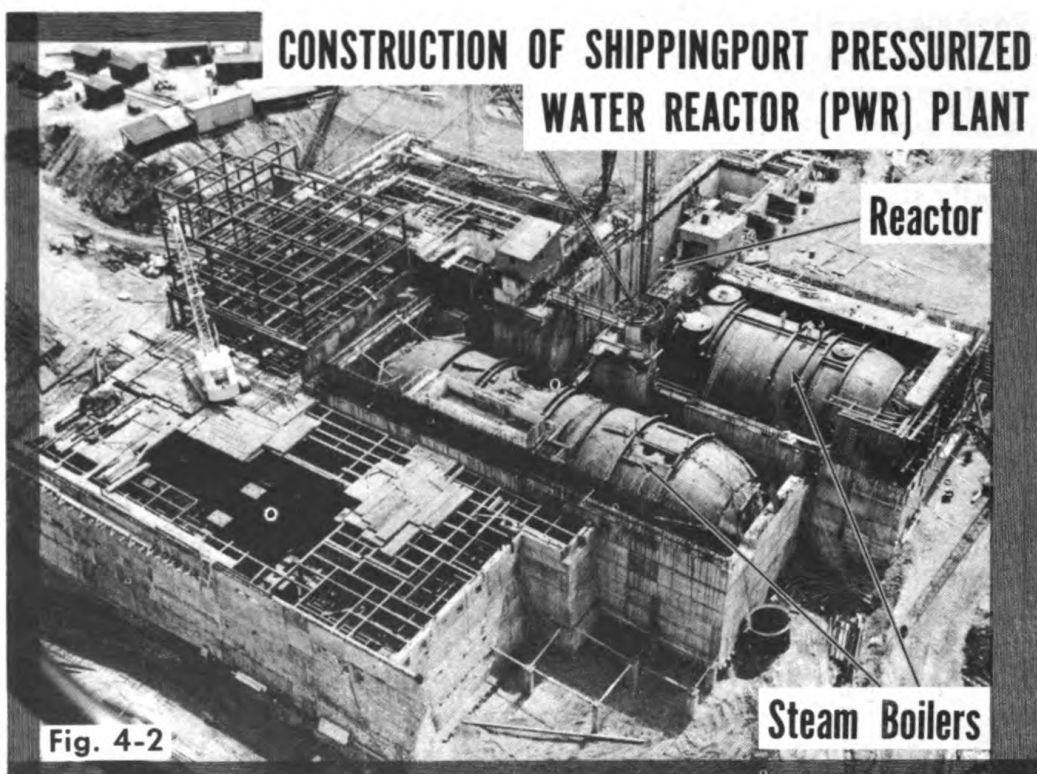
The primary advantages of pressurized water reactors are their ease of operation and comparative safety because of their negative temperature coefficient. This not only prevents the reactor from "running away," but also gives it a measure of self-regulation (adjusting of output to meet demand). If the power demand increases, for example, more steam is drawn from the heat exchanger, thus chilling the primary water coolant. Because of the negative temperature coefficient, a cooler-than-normal water flowing through the reactor core *increases* the reactivity, thus complying with the increased demand.

The major disadvantage of the PWR is that the steam it produces is loaded with water vapor (which causes erosion) and is not hot enough for efficient turbine operation. If it is attempted to increase the temperature and pressure of the steam for efficient operation, costs go up, and the plant becomes even less competitive with conventionally fueled plants.

#### Shippingport Pressurized Water Reactor

The major example of a pressurized water reactor (PWR) is the \$121 million Shippingport Atomic Power Station (Figs. 4-2 and 4-3), which

## NUCLEAR ENERGY AND POWER REACTORS



## POWER REACTORS AND PLANTS

was designed jointly by the Westinghouse Electric Corporation and the Duquesne Light Company with financial assistance from the Atomic Energy Commission. The plant has been furnishing 60,000 kilowatts of electrical power to the Greater Pittsburgh area since December 23, 1957. Although the Shippingport plant may ultimately operate at a power level close to 100,000 kw, its primary purpose is *not* to generate electricity at costs competitive with ordinary fuels, but rather to advance the technology of pressurized-water reactors.

### PWR Flow Diagram

The pressurized-water reactor provides the heat for generating electricity, as is shown schematically in the flow diagram (Fig. 4-4). Heat from the

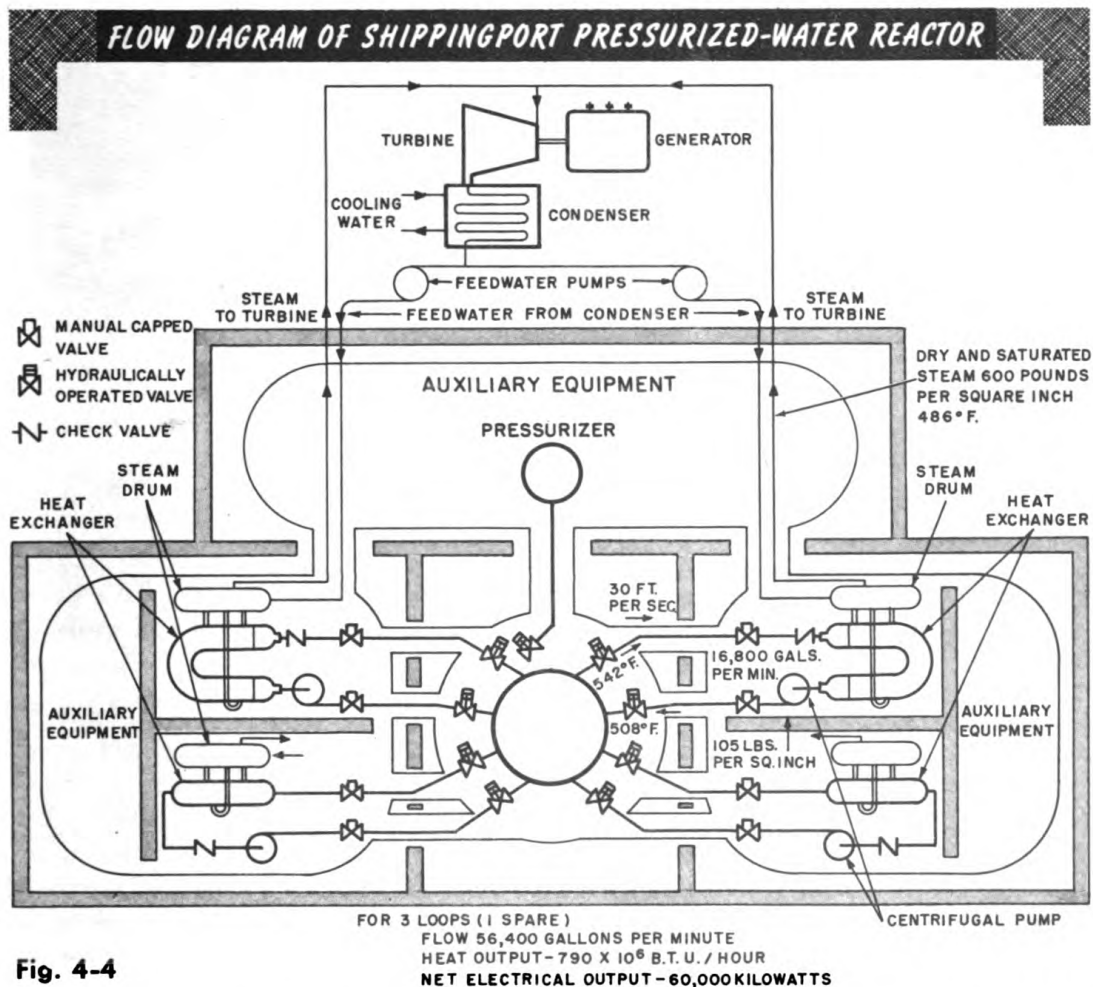


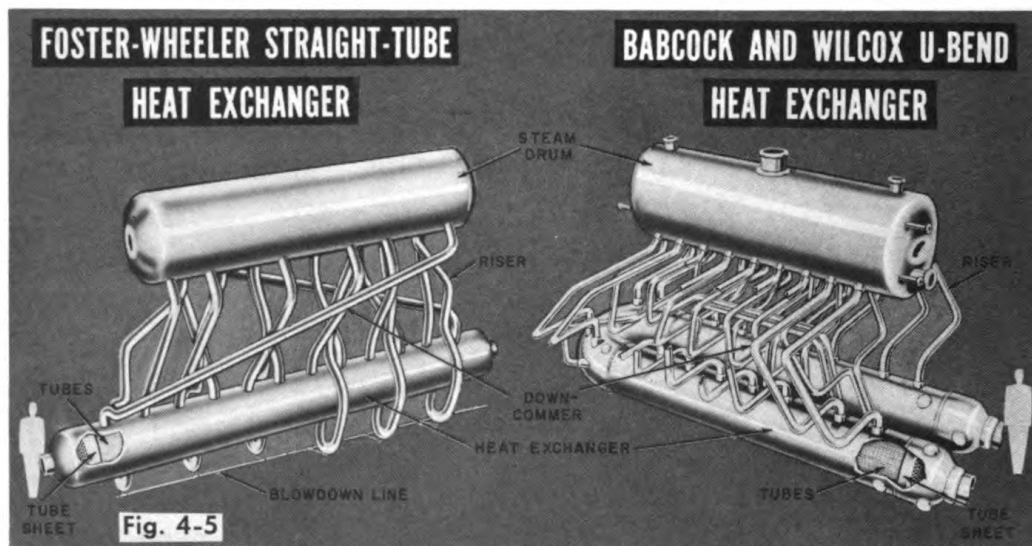
Fig. 4-4

reactor (790 million British thermal units per hour) is carried by highly purified water, circulating through three primary (radioactive) loops, to heat exchangers that serve also as steam generators. The total liquid flow

## NUCLEAR ENERGY AND POWER REACTORS

in the three primary loops is approximately 56,400 gallons per minute (gpm), with a fourth primary loop being provided as a spare.

The heat exchanger-steam generators in the primary loops (Fig. 4-5) are of two types. Two of the loops use a *straight-tube* heat exchange (manufactured by Foster-Wheeler), while the other two use a *U-bend* heat exchanger (manufactured by Babcock and Wilcox). Both types generate



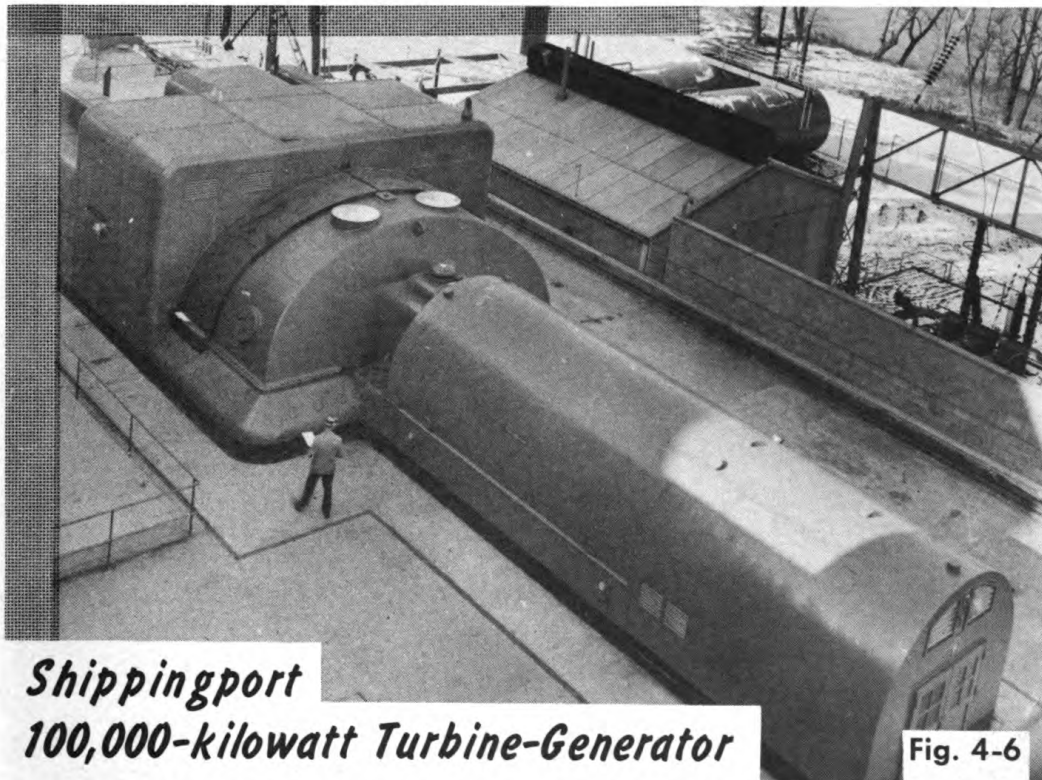
steam in the same general way. The primary water heated by the reactor flows through hundreds of small stainless steel tubes in the heat exchanger sections of the steam generators, and is returned to the reactor by a centrifugal pump, one being provided for each primary loop. The stainless steel tubes are surrounded by water of the secondary (non-radioactive) system, which is thus heated by the primary water. The wet steam formed from the secondary water, passes upward through the "risers" and enters a *steam drum* (boiler). Here the steam is dried, and the separated moisture returned to the heat exchanger through the "downcomers."

The dried steam from the boilers passes under a pressure of about 600 pounds per square inch (psi) through the secondary loops and drives the turbine-generator (Fig. 4-6), which consists of an 1800-rpm turbine and a generator rated at 100,000 kw maximum. Approximately 860,000 pounds of dried steam at 600 psi flow from the steam generators to the turbine each hour. The spent steam from the turbine exhaust is passed through a condenser, where it is cooled. The condensate (water) is returned to the steam generators by feedwater pumps.

### Reactor and Fuel Arrangement

The major components of the Shippingport PWR are the *reactor core* (with associated fuel elements, *control rods* and the *rod-drive mechanism*) and

## POWER REACTORS AND PLANTS

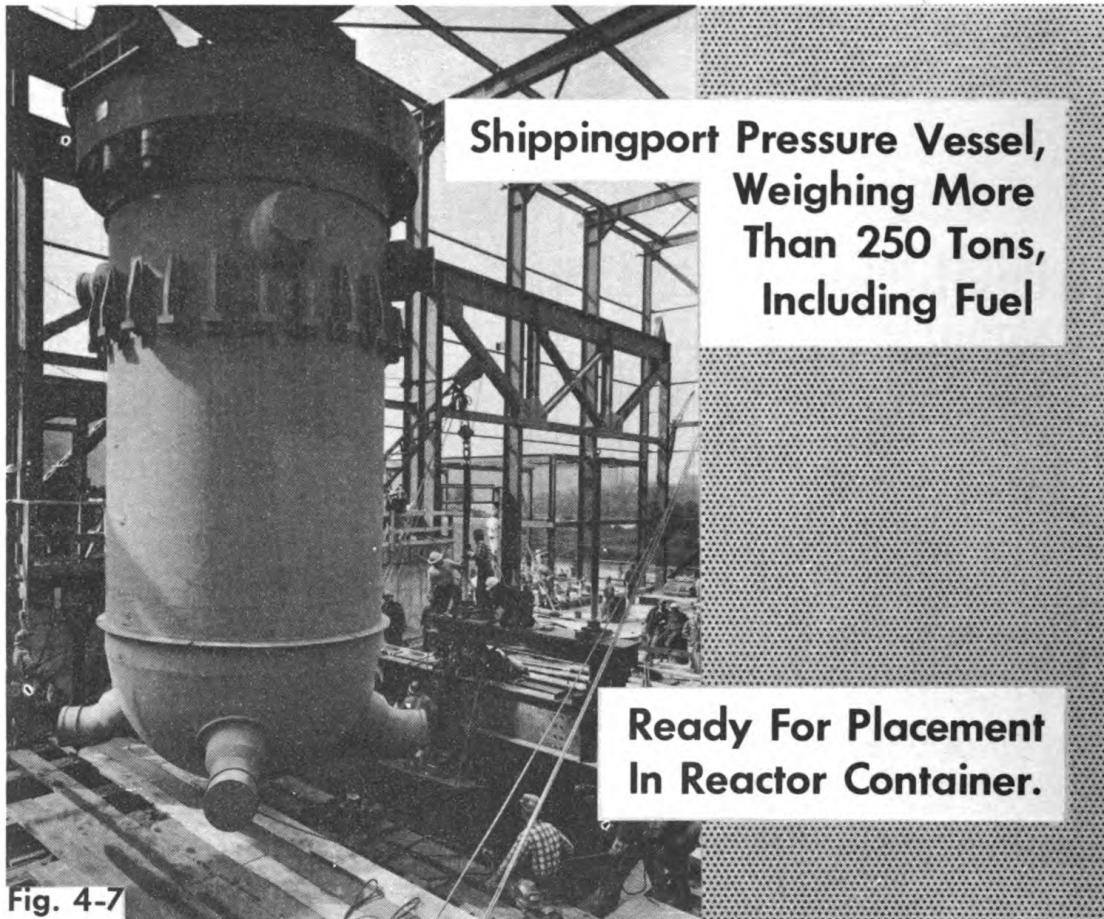


a *pressure vessel* containing the core assembly. The pressure vessel (Fig. 4-7) is a cylindrical carbon-steel container with hemispherical upper and lower ends, clad on the inside with stainless steel. It is approximately  $32\frac{1}{2}$  feet high,  $10\frac{1}{2}$  feet in outside diameter, and is designed to withstand an internal pressure of 2500 pounds per square inch. Four inlet nozzles (see Fig. 4-8) at the bottom of the vessel introduce the cooling water and four outlet nozzles, near the top, discharge the heated coolant into the primary loops.

Since radiation induces heating in the structural materials surrounding the core, two concentric stainless steel thermal shields are placed between the core cage and the inner wall of the pressure vessel. In addition, 3 feet of water surrounding the reactor vessel provide shielding against neutrons, and 5 feet of structural concrete around the pool of water make up an effective biological shield against all kinds of radiation.

The reactor core, consisting of fuel elements and control rods, is supported in a barrel-shaped *core cage* between a bottom *support plate* and a *top grid*. During operation, the cooling water enters through the inlet nozzles at the bottom, flows through a lattice of boxes in the bottom support that hold the fuel elements, and is channeled into the fuel assemblies. After being heated by its passage through the fuel assemblies, the coolant emerges through open boxes in the top grid and exits through the outlet nozzles.

## NUCLEAR ENERGY AND POWER REACTORS



A *core hold-down barrel* is provided to prevent the upward thrust of the cooling water from lifting the core out of position.

A *seed-and-blanket design* (Fig. 4-9) was chosen for the active section of the reactor core, since this arrangement uses a minimum of enriched uranium (U-235) and permits extensive use of natural uranium (U-238). The seed fuel is principally uranium-235, the blanket fuel natural uranium dioxide ( $\text{UO}_2$ ). Initially, it is the U-235 seed fuel that makes it possible to start and maintain the nuclear chain reaction. At start-up with a new core about 50 percent of the power is derived by fission in the natural-uranium blanket: this percentage is higher at the end of the core life. The reason for this behavior is that during operation a portion of the neutrons produced by the fissioning U-235 seed is absorbed by the natural uranium (U-238) blanket. You will recall (from chapter 2) that this process converts U-238 into *plutonium-239*, which is also fissionable by thermal neutrons. Thus, plutonium fission is added to that of uranium-235 as a source of energy. Moreover, since the quantity of plutonium builds up during the life of the core, the blanket material will produce an increasing proportion of the overall power by burning plutonium in place of the U-235.

## POWER REACTORS AND PLANTS

### LONGITUDINAL SECTION THROUGH PWR PRESSURE VESSEL AND CORE

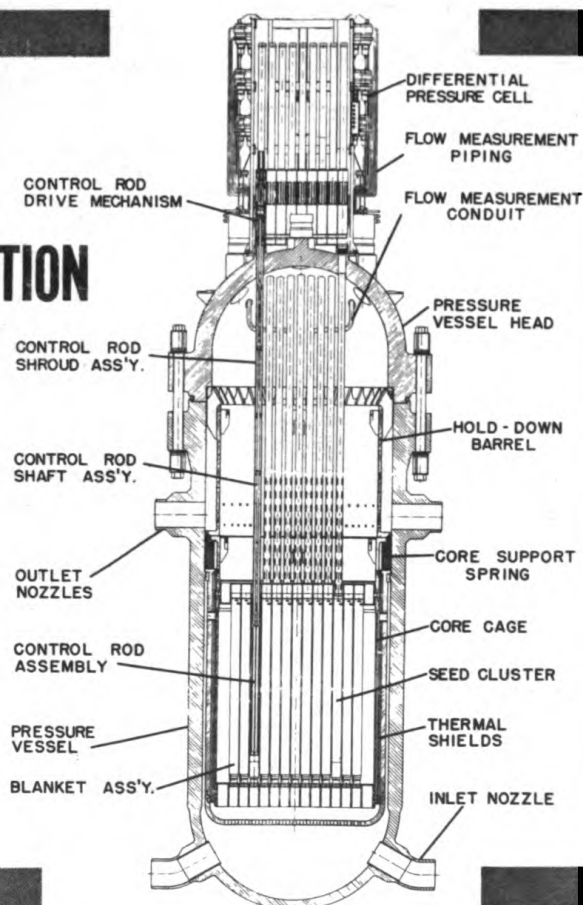


Fig. 4-8

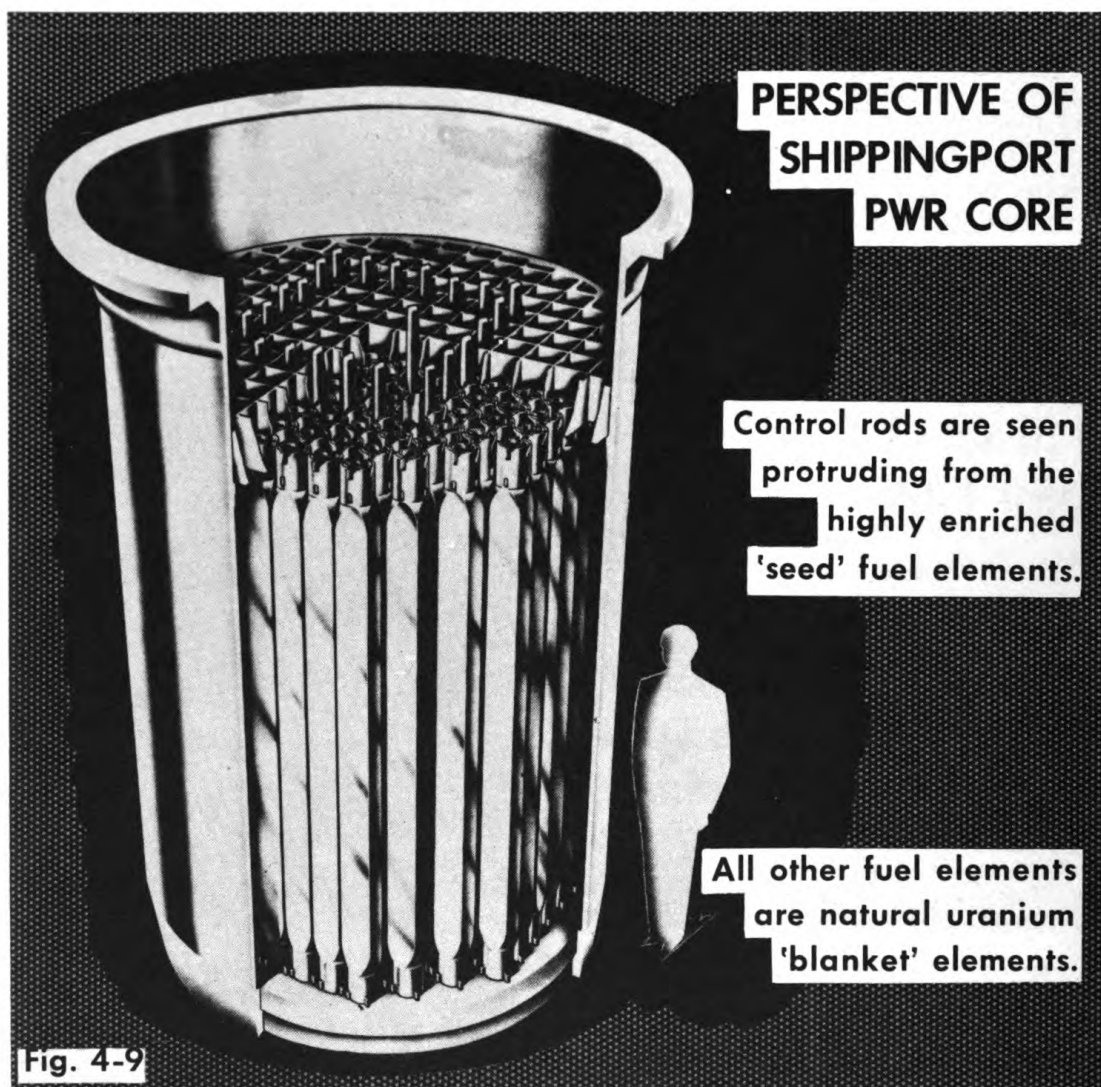
Of the 145 fuel assemblies, 32 are the highly enriched seed assemblies, which are arranged in a hollow square with blanket assemblies both inside and outside the seed. Each seed assembly is about  $5\frac{1}{2}$  inches square in cross section and about 70 inches long. The seed fuel, principally U-235, is alloyed with zirconium to form the "meat" in a sandwich that is clad on the outside with *Zircaloy* (an alloy of zirconium). This is rolled into thin plates, which are separated by narrow passages to allow the flow of cooling water. The seed fuel contains a total of approximately 165 pounds of uranium-235.

The natural uranium-dioxide blanket fuel is contained in 113 blanket assemblies, 45 inside and 68 outside the hollow square of seed assemblies. As shown in Fig. 4-10, 26 cylindrical pellets of uranium dioxide are sealed in 10-inch long fuel rods, made of *Zircaloy*. Each blanket assembly contains seven bundles of 120 fuel rods each, stacked one above the other.

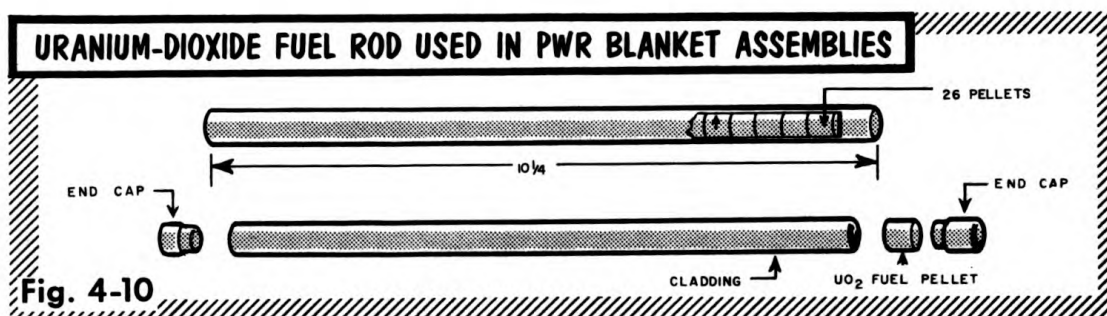
#### Control and Instrumentation

An important advantage of the seed-and-blanket design in the PWR is that it concentrates the enriched uranium in the seed, thus reducing the area

## NUCLEAR ENERGY AND POWER REACTORS



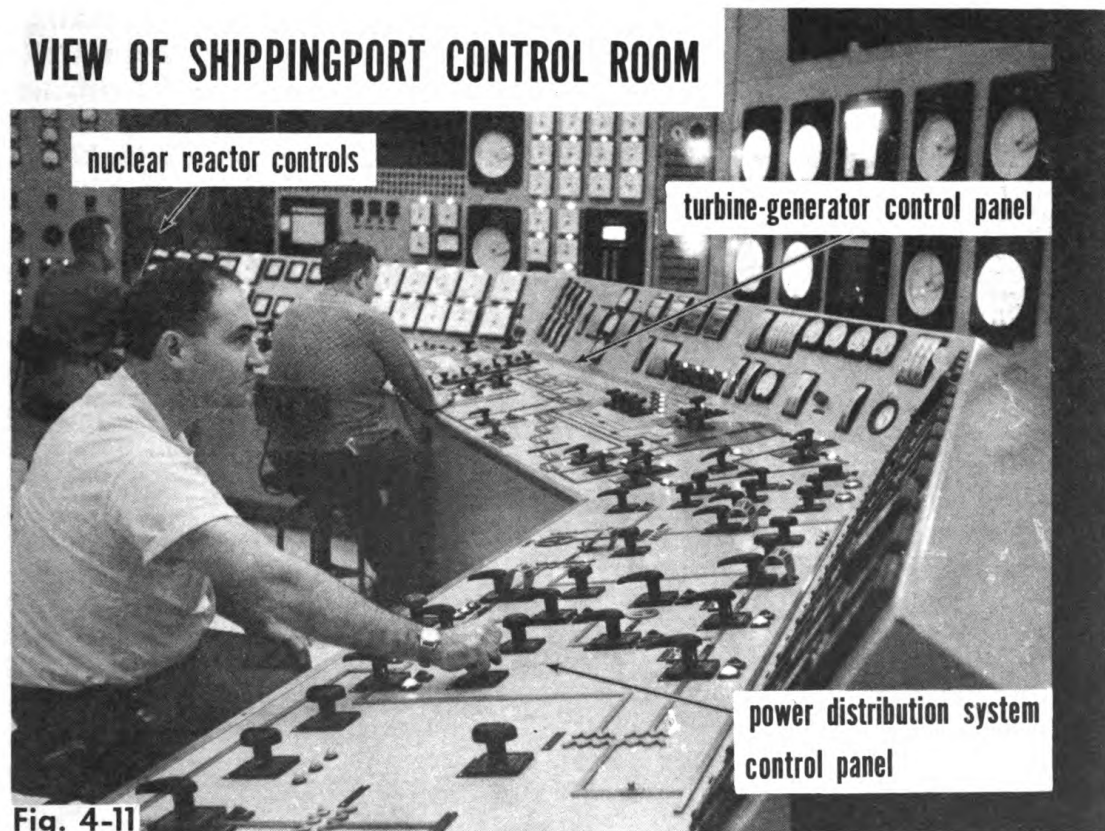
that must be controlled by control rods and associated mechanisms. Each of the 32 seed assemblies is provided with a cross-shaped channel, which permits an equal number of hafnium control rods to move in and out of the assemblies. The control rods are connected by special shafting to drive



## POWER REACTORS AND PLANTS

mechanisms located in the head of the pressure vessel. No control rods are needed for the blanket assemblies.

In addition to the control rods, which are operated from a console panel in the central control room (Fig. 4-11) the Shippingport pressurized water reactor is extensively instrumented to provide information for plant operation, warning operators in case of fuel assembly damage, and compiling data for designing future reactors. Only the *sensing elements* of the instruments are in the reactor itself. The measurements are metered on the nuclear reactor (core) panel in the control room.



The reactor instrumentation includes *thermocouples*, *flow meters*, and *failed-element detection and location* (FEDAL). Thermocouples measure inlet and outlet coolant temperature in representative fuel assemblies to assist in calculating the power output. Other thermocouples measure fuel-plate temperature in some of the seed assemblies. The cooling water enters the fuel assemblies through special flow-metering orifices, which are connected through tubes to external *differential pressure cells*. These cells transmit signals regarding the fluid velocities to flow meters, which in conjunction with the inlet and outlet temperature measurements, permit calculating the power produced in the fuel assemblies.

## NUCLEAR ENERGY AND POWER REACTORS

The FEDAL system permits detecting and locating faulty blanket fuel elements, which might be corroded or punctured, thus releasing radioactive materials into the coolant. The outlet end of each blanket assembly is equipped with a rake for sampling the coolant exit water. The sample flows from each rake to an external detection system, which permits checking the radioactivity and locating defective assemblies, and is then returned to the reactor coolant system.

### Refueling and Handling

The pressurized water reactor allows fuel to be replaced in either of two ways. One is to remove and replace the whole core, which requires taking the closure head off the pressure vessel. The other is to remove and install individual fuel assemblies by working through the fuel ports without removing the head. Since either operation involves handling highly radioactive materials, the work is done under water, by using remotely controlled handling equipment. To minimize radiation exposure of operating personnel and to permit visual observation of inaccessible areas, closed-circuit television and optical viewers are used. Remote viewing by means of closed-circuit television is used extensively throughout the Shippingport plant. In addition to remote viewing of refueling, an adjustable-focus TV camera is located in each of the four boiler compartments and one in the pressurizer compartment. A monitoring receiver in the control room can be switched to any one of the five cameras. There are also four fixed-focus TV cameras, adjusted to view the four boiler-drum-level gage glasses, with associated television monitors in the control room.

### Safety and Radiation Monitoring

Basically, the approach at Shippingport has been to design and build highly reliable barriers for containing radioactive material and then to provide protection against all conceivable accidents that might release radioactive fission products through these barriers. Two independent and continuously monitored barriers between the fission products and the surrounding area are incorporated into the pressurized water reactor design. First, all fission products are contained within the fuel elements themselves, which are clad in corrosion-resistant zirconium alloys. The second containment barrier is provided by the cooling water (primary system) circulating past the fuel elements in an all-welded pressurized system. Should fission products from faulty fuel elements leak into the water, they will be contained in the primary coolant system, which is continuously monitored by FEDAL.

In addition, there is yet a third independent barrier: the entire reactor plant of the pressurized water reactor is housed in a group of interconnected, vapor-tight steel pressure vessels, known as *reactor-plant containers*.

An analysis of all possible accidents that might threaten the safety of the plant, leads to the following conclusions:

## POWER REACTORS AND PLANTS

1. Should an explosion occur in the pressurized water reactor, there would be no physical, chemical or nuclear hazard outside the site.

2. A *reactor-protection system* prevents any damage to the core. No combination of pump failures or other loss of coolant flow can release fission products. Even a complete loss of electrical power would not constitute a hazard to personnel.

3. The inherent stability of the PWR (due to its negative temperature coefficient) precludes any nuclear power excursion that would result in vaporizing or gross melting of the fuel elements with an attendant explosive pressure build-up in the cooling system.

4. Complete release of the reactor coolant to the outside atmosphere would not result in a biological hazard beyond the site, even if the core had been operating at full power for its normal life (3000 hours) and the coolant were loaded with maximum radioactivity due to as many as 1000 leaky elements.

5. A major rupture in the reactor cooling system resulting in complete loss of coolant in the only accident that could release a significant amount of radioactive fission products within the plant. In the improbable event of such an accident, a *safety injection system* would be able to pump sufficient water into the reactor cooling system to prevent core melting and subsequent development of a biological hazard beyond the site. Moreover, the PWR reactor plant container can adequately withstand the maximum pressure that could develop for the most extreme rupture in the coolant system.

A major design feature of the Shippingport plant is the safeguarding of operating personnel and people in the surrounding area against any ill effects from the nuclear radiation given off by the reactor and contaminated cooling water. Operating personnel are protected from direct radiation by heavy 4½-foot-thick concrete walls surrounding all parts of the plant and by a 3-foot-thick water tank surrounding the reactor pressure vessel. An extensive set of instruments continuously monitors the direct radiation in the plant, as well as the radiation from the cooling water, the waste disposal system, and the surrounding atmosphere.

Radiation is monitored throughout the plant by two separate systems, one for measuring the power level, the other for safety. The power-level (operational) monitoring system provides the information needed for operating the plant within permissible radiation levels specified by the A.E.C. This system has 12 channels, each containing one or more detectors, a pre-amplifier where necessary, and a computer-indicator to provide read-out information. The computer indicator units are located in the *radiation monitoring panel* of the main control room, the detectors throughout the reactor plant. The functions of the channels and detectors are as follows:

1. Four channels with gamma-sensitive Geiger tubes, one in each steam generator, detect leakage of primary cooling water into the secondary

## NUCLEAR ENERGY AND POWER REACTORS

system. (Leakage is indicated by abnormal radioactivity in samples of secondary cooling water.)

2. Four gamma-sensitive ion chambers monitor radioactivity in each of the four boiler chambers.

3. A gamma-sensitive Geiger tube monitors the water used to cool pumps, control-rod drive motors, heat exchangers, and other components. (This cooling water might become contaminated by leakage of primary cooling water.)

4. Four beta/gamma-sensitive Geiger tubes monitor the radioactivity of gases and airborne particles in the air exhaust stack of the plant.

5. Four channels use a filter-paper system and scintillation counters to monitor the activity of the air within the plant.

6. Monitors check six cubicles with limited personnel access.

The safety radiation monitoring system detects any dangerous increase in the normal background of the plant surroundings. This system includes all on-site and off-site equipment necessary to locate and measure radiation hazards. Areas within the plant normally occupied by personnel are monitored to warn against increases in radiation levels. Hand and foot monitors are used in various buildings and monitors are provided at the exits. Film badges and dosimeters are provided for all personnel to record cumulative doses of radiation. In addition, a program of continuous monitoring of the environment outside the plant buildings utilizes integrating ionization chambers, mobile off-site monitoring stations, and river sampling stations. Finally, there is extensive monitoring of the radioactive-waste disposal system, comprising 14 detectors in four separate channels. These monitors indicate radiation levels in liquid and gaseous hold-up tanks, in the evaporator, and other disposal channels, guiding proper discharge rates.

### Radioactive-Waste Disposal

Most PWR radioactive wastes come from the reactor cooling system. As water circulates through the fuel elements of the reactor core, small amounts of radioactive corrosion products make it slightly radioactive. In addition, fission products from leaky fuel elements are released into the primary coolant. The radioactive-waste disposal system was designed to operate satisfactorily with as many as 1000 failed (leaky) uranium-oxide blanket-fuel tubes. It is highly unlikely that any of the enriched uranium seed fuel elements will rupture, since they are of a highly developed design. Moreover, radioactive-waste disposal is relatively simple at Shippingport, since spent fuel elements are not chemically processed at the plant site, but are shipped elsewhere.

The radioactive material consists of liquid, solid, and gaseous wastes. All of these wastes are transported to a processing area adjacent to the reactor

## POWER REACTORS AND PLANTS

plant, segregated, processed or stored, and ultimately disposed of, as shown in Figs. 4-12 and 4-13. As shown in Process Flowsheet No. 1, the reactor plant liquid outflow (called *effluent*) is piped to underground stainless-steel tanks surrounded by watertight concrete enclosures, where it is monitored for radioactivity. Depending on the degree of radioactivity, the waste liquid may be stored in the tanks while the radiation tapers off, or it may be processed through *demineralizers* and a *gas stripper* that removes radioactive gases. If the wastes are within permissible radiation limits, the liquid is blended with the condenser-cooling steam and discharged into the Ohio river.

Soluble radioactive impurities and particles are removed in a series of mixed bed demineralizers. The processed liquid is sampled in test tanks to assure that it is within allowable radiation tolerances when diluted with the condenser-cooling-water stream. Dissolved fission gases are stored in steel (gas decay) tanks until their activity has tapered off enough to permit safe discharge into the atmosphere from the stack. Other liquid and gaseous outflows are monitored before discharge into the atmosphere, and re-processed if required.

Fluids used for decontaminating equipment containing highly concentrated radioactive impurities are processed through a *vapor-compression evaporator*. The distillate from the evaporator is sent to *surge tanks* and the concentrate is mixed with cement and passed through drums for burial in the ocean. As shown in Fig. 4-13, the spent demineralizer resin used for the internal water purification system is diverted by a stream of water to permanent underground stainless-steel storage tanks, in which the solids settle. These tanks are surrounded by a waterproof concrete enclosure. The water used to transport the resin is spilled into liquid decay tanks for further processing.

Combustible, contaminated solid wastes, such as paper, rags, and clothes, are incinerated. Gases from the combustion process are scrubbed and filtered to remove airborne particles. Ashes and wash water are then fed to the resin-storage tank.

Non-combustible solid wastes, such as contaminated tools, metal turnings, and small equipment, are placed in 30-gallon drums and sealed. These, in turn, are placed into larger drums and shielded by pouring concrete between the drums. The drums are then shipped for ocean burial. Pieces of equipment too large to ship are handled by remote control and suitably buried in a "graveyard" at the site.

### Consolidated Edison Thorium Reactor

Before going on to other types of power reactors, let us mention two other pressurized-water reactors, which are in an advanced stage of construction. They are the Con Edison thorium reactor at Indian Point, N.Y., about 24 miles north of New York City, and the Yankee Atomic Power Plant at Rowe,

# NUCLEAR ENERGY AND POWER REACTORS

## SHIPPINGPORT RADIOACTIVE WASTE DISPOSAL SYSTEM, PROCESS FLOWSHEET No. 1

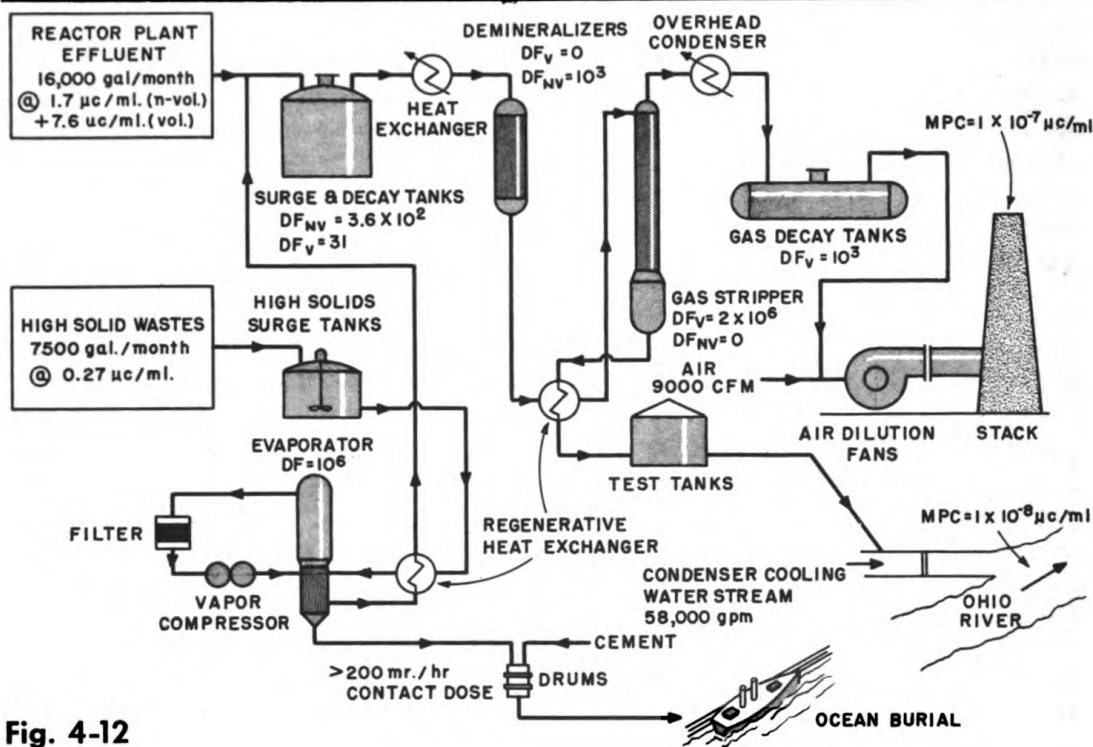


Fig. 4-12

## SHIPPINGPORT RADIOACTIVE WASTE DISPOSAL SYSTEM, PROCESS FLOWSHEET No.2

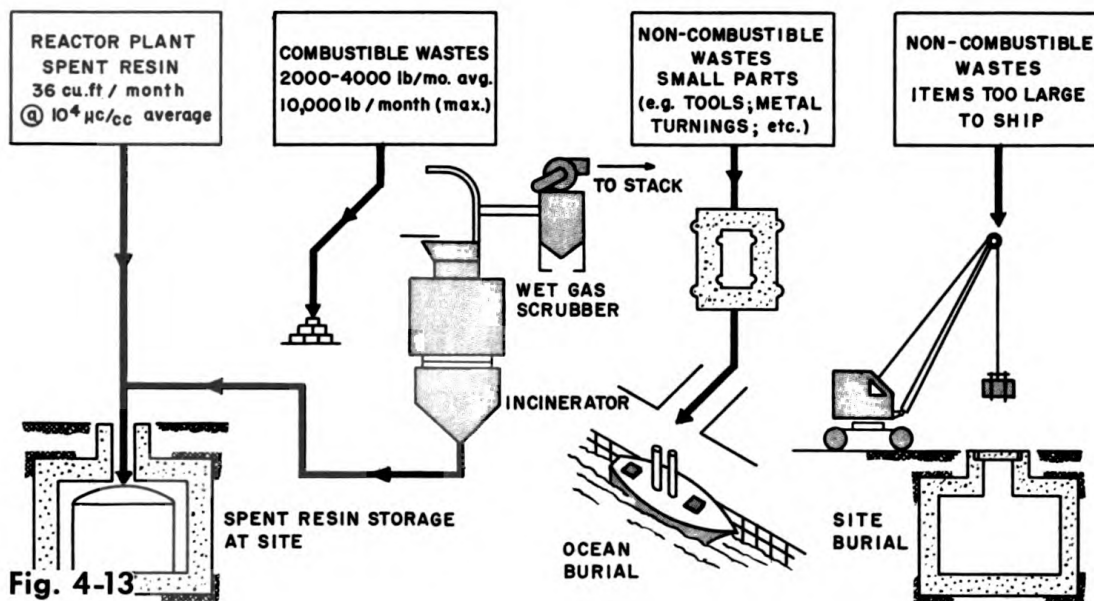


Fig. 4-13

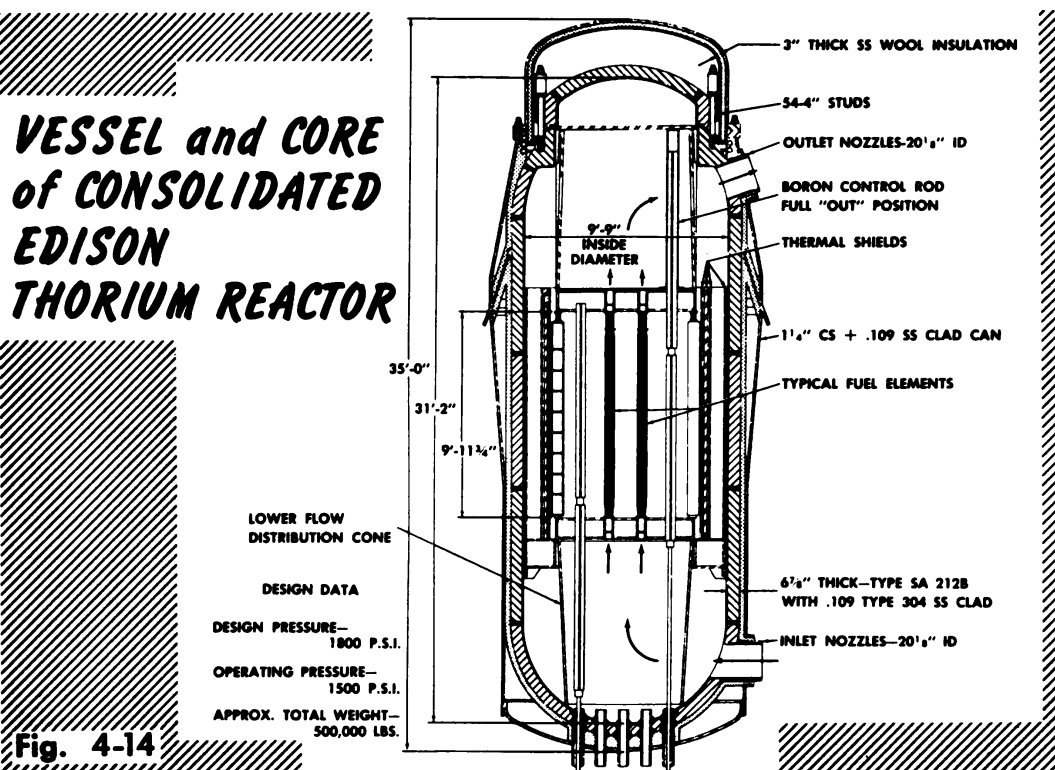
## POWER REACTORS AND PLANTS

Mass. The Con Edison Plant, particularly, shows some interesting design differences from the Shippingport reactor.

Designed for an ultimate gross electrical capacity of 275,000 kilowatts (275 megawatts), construction on the Con Edison reactor began in 1956 and the plant is scheduled to be completed in late 1960. What makes the Con Edison reactor particularly interesting is that it is designed as a "thorium converter," which transmutes thorium-232 into uranium-233, in accordance with the nuclear reaction described in Chapter 2. The core of the reactor will initially contain about 850 kilograms of fully enriched U-235 and as much as 17,400 kg of thorium oxide. At the end of the useful core life—about 600 days at full power—a small amount of thorium will have been converted into 146 kilograms of fissionable U-233, thus supplementing the original fuel loading. The reaction will also produce some 14.6 kilograms of protactinium, which is not useful as a fuel. To produce the electrical output of 275 megawatts, the reactor must attain a thermal power of 1,706,500 Btu per hour (500 megawatts), which results in an electrical output of 163 megawatts. (An oil-fired superheater provides 112 megawatts supplementary energy.)

### Reactor Core and Vessel

The Con Edison reactor is housed in a 160-foot carbon-steel sphere with inch-thick walls, and enclosed by a cylindrical concrete radiation shield. In the center of the sphere is the reactor pressure vessel, shown in Fig. 4-14.



## NUCLEAR ENERGY AND POWER REACTORS

The vessel is surrounded by a neutron-shield tank and a concrete biological shield.

Like the Shippingport reactor, the Con Edison PWR employs a primary coolant system and a secondary steam system that drives the turbine-generator via the superheater. The heat generated in the reactor is transferred by pressurized water to four steam generators in the primary system. Some 100,000 gallons per minute of pressurized water are needed to carry away the heat generated in the reactor core. The water enters the pressure vessel through an inlet at about 482°F, is directed past the fuel elements and control rods, and leaves the outlet at about 510°. An automatic control system operates a regulating rod to maintain steam pressure at 420 pounds per square inch for a steady load. Two oil-fired superheaters further improve the steam temperature and pressure at the turbine inlet adding 112,000 kilowatts electricity to the turbine generator capacity.

The reactor vessel is a cylindrical shell of carbon steel, with an inside diameter of 9.75 feet and a minimum wall thickness of almost 10 inches. The active core, containing some 120 fuel elements and 21 control rods, measures about 6½ feet in diameter and is 8 feet high. The uranium-oxide/thorium-oxide fuel mixture and the flow of pressurized water takes up about 72 percent of the core volume, the remainder being occupied by stainless steel and Zircaloy-2 structural materials. The drive assemblies for the 21 control rods are located beneath the reactor vessel.

### Yankee Atomic Electric Company Plant

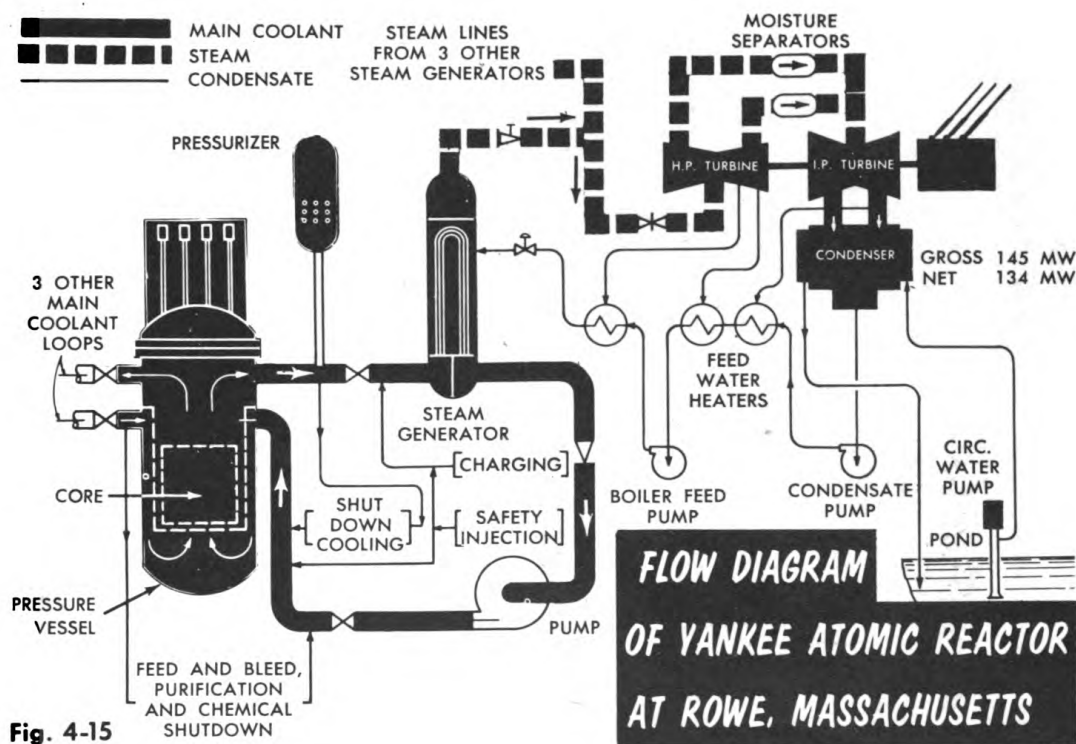
The Yankee plant, under construction at Rowe, Mass., will have a net electrical capacity of 134,000 kilowatts at its completion in 1960. The Yankee Atomic Electric Company will operate the power plant and bear all construction costs—estimated at \$50 million with the AEC assisting in research and development costs. The heart of the plant will be a pressurized-water reactor, water-cooled and moderated, employing 2.6% enriched uranium fuel elements clad with stainless steel. The fuel will be some 27,000 kilograms of uranium dioxide pellets in stainless-steel tubes. Reactor design and operation is similar to Shippingport.

The Yankee plant circulates water, at a temperature of about 500°F and at 2000 pounds pressure per square inch, from the reactor vessel through four piping loops and four steam generators. One of these loops is shown in Fig. 4-15. The principal equipment in each loop consists of two gate-type valves, a steam generator-heat exchanger, a circulating pump, a check valve, and a relief valve.

### Experimental Boiling-Water Reactor (EBWR)

In the boiling-water reactor, the steam that drives the turbo-generator is generated *directly* in the reactor core. This eliminates at one stroke the highly pressurized cooling water and associated pumps and heat exchangers

## POWER REACTORS AND PLANTS

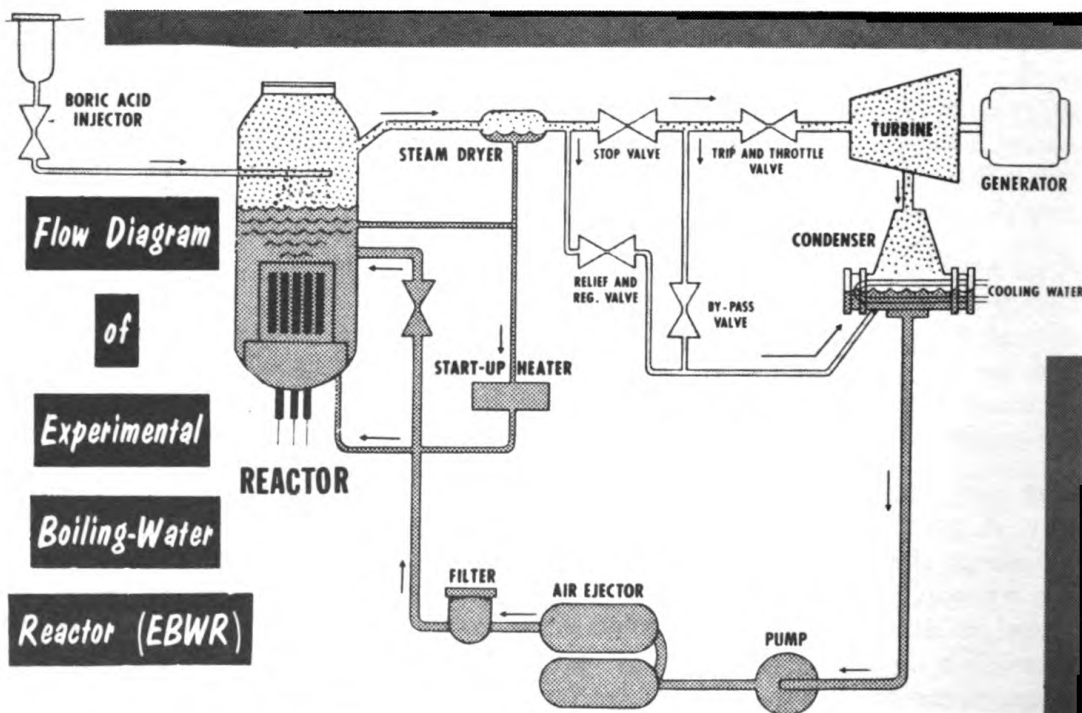
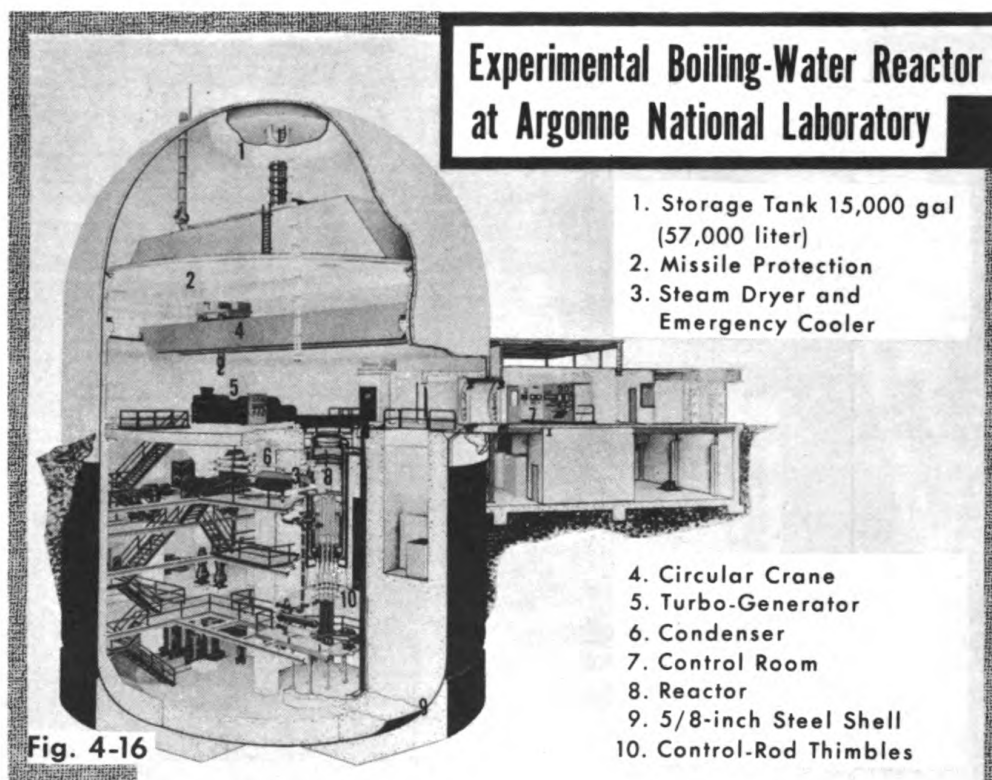


that make the PWR such an uneconomical unit. It also permits the generation of turbine steam at far higher pressure and temperature than is possible in a pressurized-water reactor. The price that has to be paid for this increased efficiency and attendant lower cost, is the carry-over of radioactive steam to the turbine with the resulting corrosion problems and the difficulty of obtaining reliable fuel elements that can withstand the conditions in the reactor core.

An experimental boiling-water reactor (Fig. 4-16), designed to produce 20,000 kilowatts of heat and 5,000 kilowatts of electricity, has been in operation at the Argonne National Laboratory since late 1956. This power level—and as we shall see later considerably higher ones—are achieved with a neutron flux of  $10^{13}$  neutrons/cm<sup>2</sup>-sec and a steam pressure of 600 pounds per square inch at 488° F.

The flow diagram of the EBWR (Fig. 4-17) shows its simplicity of operation. A start-up heater begins the natural circulation of the moderator/cooling water through the reactor core. The water is brought quickly to a boil by the operating reactor, and is transformed into high-pressure steam. The steam is dried to remove the water vapor and is then fed to the turbine through a system of valves that permit relief of excess pressure. The spent steam from the turbine is cooled by a condenser and the condensed water is pumped back to the reactor through an air ejector and filter. The boric acid injector is provided to permit quick dousing of the reaction if necessary.

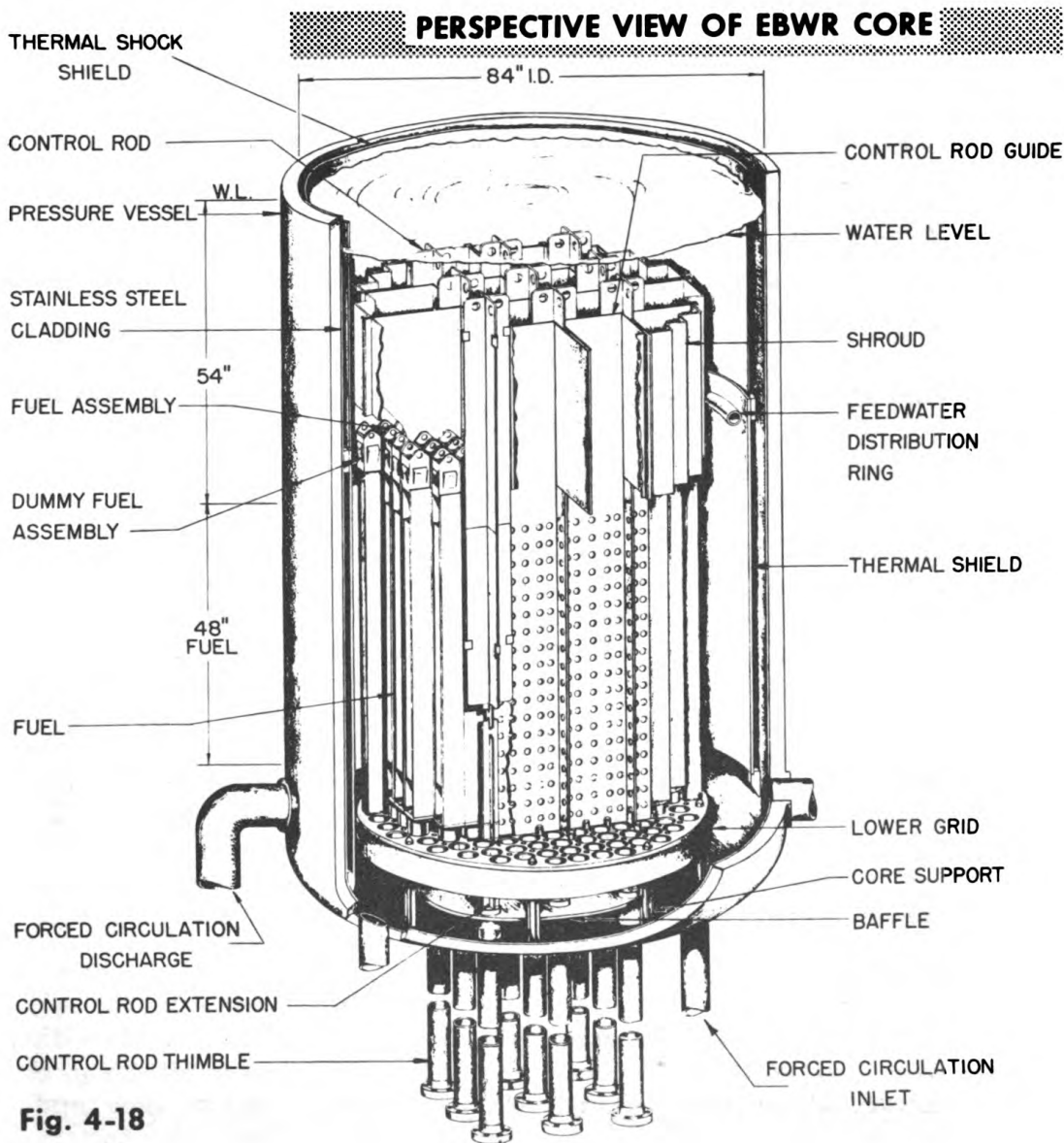
## NUCLEAR ENERGY AND POWER REACTORS



**Fig. 4-17**

## POWER REACTORS AND PLANTS

The core of the EBWR (Fig. 4-18) is a right cylinder that contains natural- and enriched-uranium fuel elements of the box type, similar to those of the BSR (pool) reactor. Each box assembly holds six fuel plates made of a zirconium-uranium-niobium sandwich, clad with Zircaloy-2. Control of the reactor is achieved by five hafnium/Zircaloy and four boron/stainless-steel rods, which are operated from a control-rod room *below* the reactor. The reactor core is surrounded by a 9-inch thickness of water, serving as reflector, a 1-inch stainless-steel thermal shield and the reactor pressure vessel, also made of stainless steel. The pressure vessel is placed in a water-cooled 3-inch-thick lead tank, which is surrounded by 7½ feet of concrete for complete biological shielding.



**Fig. 4-18**

## NUCLEAR ENERGY AND POWER REACTORS

A year of experimentation with the EBWR has brought some remarkable improvements. Although it was originally designed for a 20,000-kilowatt heat level, which was achieved in December 1956, this level was stepped up 3 times, to 62,000-kilowatts of heat, without any change in the physical plant. The high heat level, which corresponds to about 15,000 kilowatts of electricity, was achieved by boiling the water in the core at a higher-than-normal rate, resulting in faster circulation and more rapid removal of heat. The step-up in power reduced the power cost by nearly 40 per cent, from an original figure of 52 mils/kilowatt-hour to 32 mils, the lowest nuclear-power cost achieved thus far. Further step-ups are considered possible.

### Vallecitos Boiling Water Reactor

A direct-cycle boiling-water reactor generating some 5000 kilowatts of electrical power has been operating successfully since October 1957 near Pleasanton, Calif. This plant is part of the General Electric Company's Vallecitos Atomic Laboratory, located about 40 miles southeast of San Francisco. Built to test the boiling-water reactor concepts developed with the EBWR, the Vallecitos reactor may be run either as a single- or dual-cycle plant. The reactor serves as a pilot project for the large 180,000 kilowatt Dresden Plant, now being constructed by General Electric.

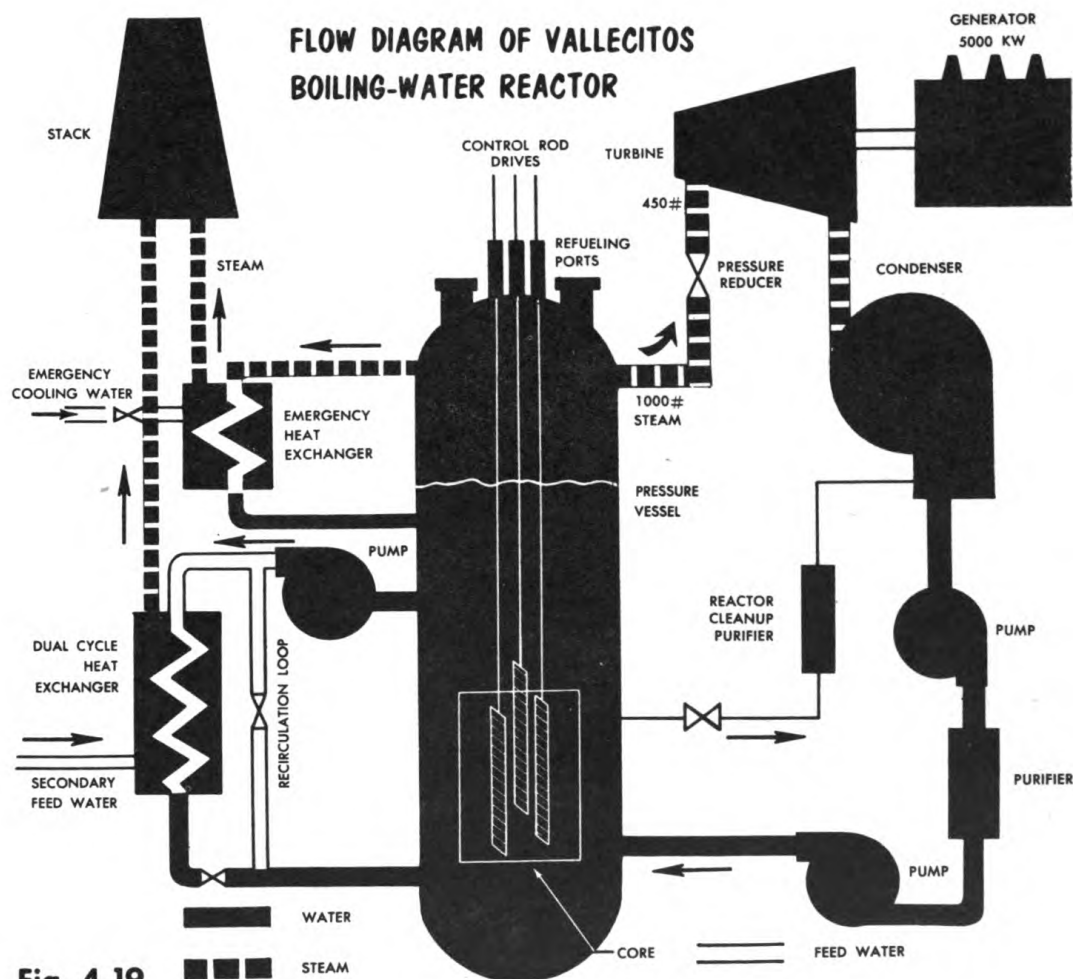
The simplified flow diagram (Fig. 4-19) shows the flexible features of the Vallecitos plant. For conventional single direct-cycle operation, the steam accumulating above the water in the reactor vessel is piped to the turbine, where it gives up its energy by expansion. The turbine drives the 5000-kilowatt electric generator, while the spent steam is liquefied in the condenser, and pumped back into the lower portion of the reactor.

When the reactor is operated as a dual-cycle system, the direct cycle takes place as before, but in addition, heat is removed from the boiling water of the reactor by a dual-cycle heat exchanger. Secondary feed water piped through this exchanger is thus converted into steam, which at present is discharged from a stack. In routine power-plant operation, this steam would, of course, be utilized by being fed into the turbine at a point about midway (in pressure). An emergency system also is provided for dissipating reactor steam whenever steam generation exceeds the capacity of the single-cycle equipment. This heat-dissipation system operates like the dual-cycle system. Externally supplied emergency cooling water is converted into steam by the reactor heat in the emergency heat exchanger and the waste steam is exhausted from the stack.

### Dresden Nuclear Power Station

The Vallecitos boiling water reactor and the A.E.C. experimental boiling water reactor (EBWR) at Argonne provided the research data for the 180,000-kilowatt \$45-million Dresden Nuclear Power Station, now under construction at a 950-acre site southwest of Chicago. Designed and con-

## POWER REACTORS AND PLANTS



**Fig. 4-19**

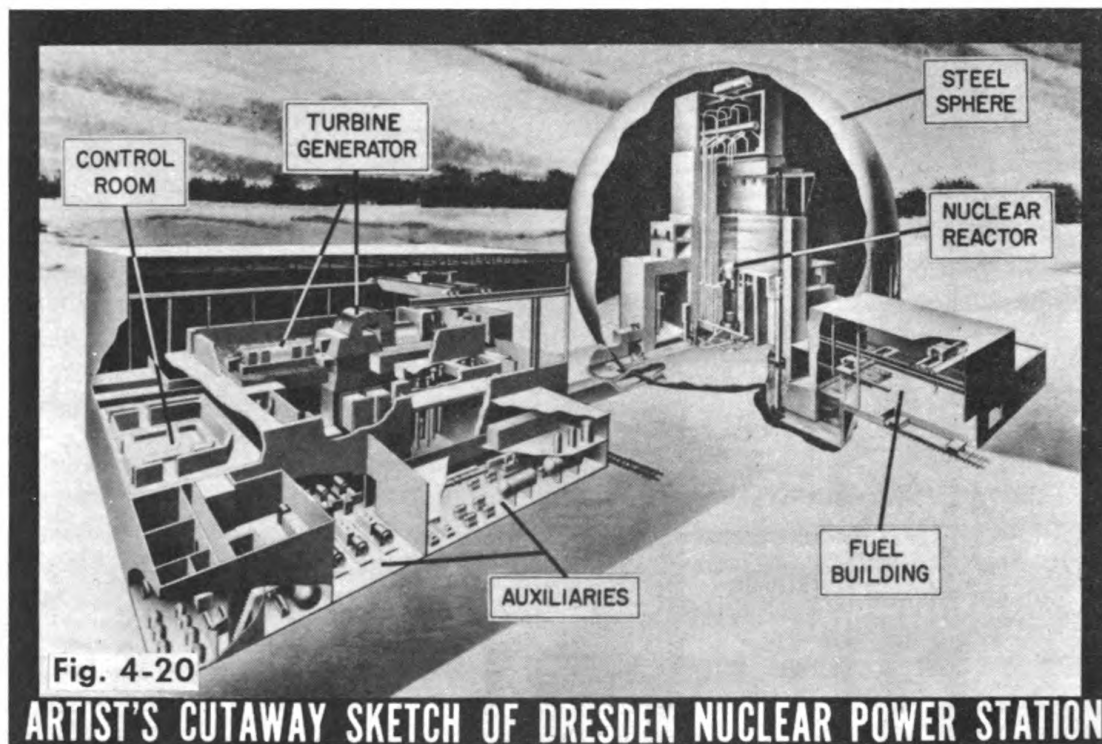
constructed by the General Electric Company under contract with the Commonwealth Edison Company of Chicago, the Dresden plant is scheduled for completion in late 1959.

The artist's cutaway sketch (Fig. 4-20) shows the location of the various facilities at the Dresden Nuclear Power Plant. A spherical building, 190 feet in diameter, contains the reactor, the steam separating drum, secondary steam generators, pumps, and other auxiliaries, making up the steam generator "package." A separate building houses the turbine-generator and auxiliary equipment required for converting the thermal energy of the reactor into electrical energy. The entire plant is operated from a control room in the west end of the turbine building. A fuel building near the reactor provides facilities for inspecting and storing new and spent fuel.

### Reactor Vessel and Core

Figure 4-21 shows the carbon-steel reactor vessel, which is 40 feet high and has an internal diameter of about 12 feet; it is lined on the inside with stain-

## POWER REACTORS AND PLANTS



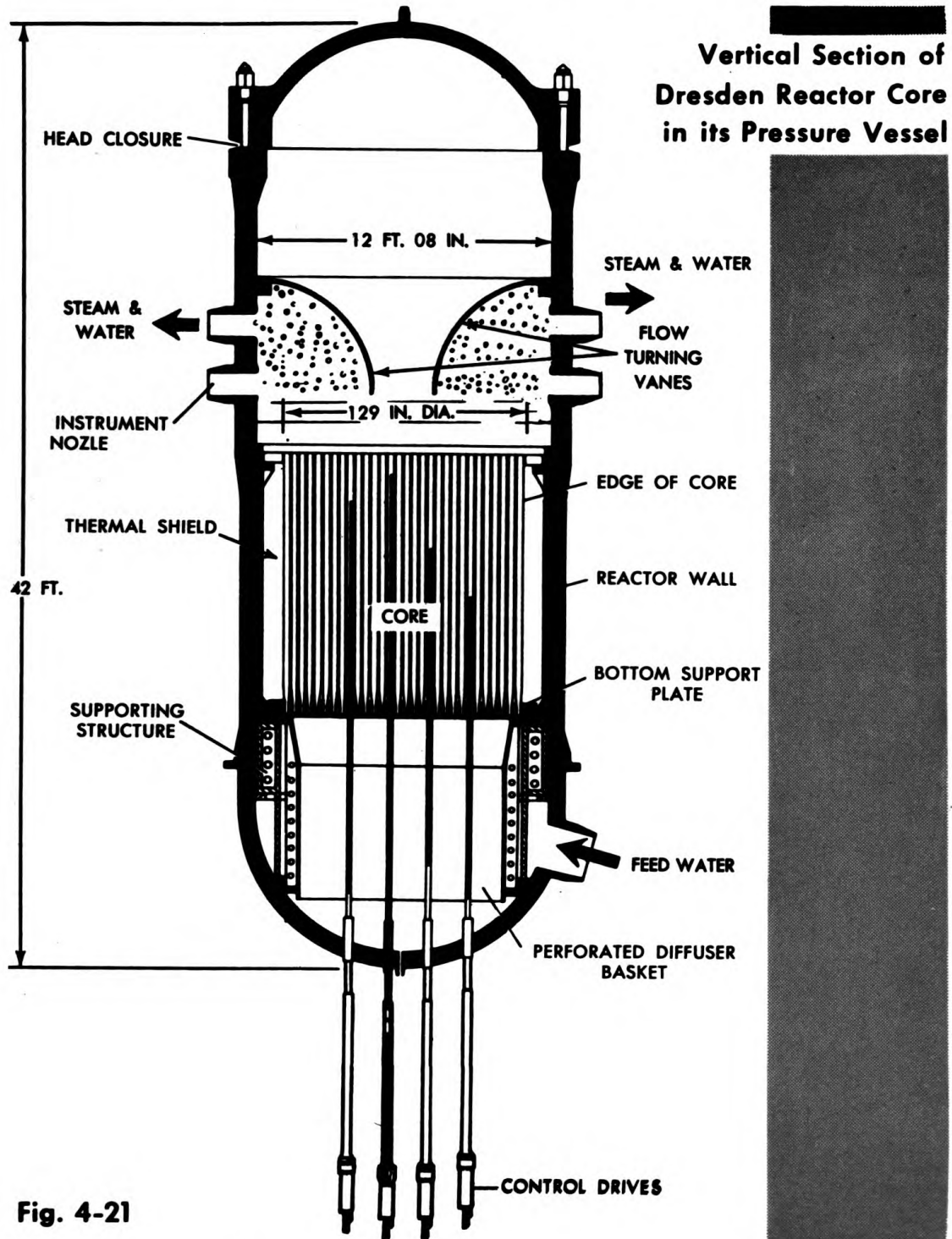
less steel. Boiling water produced by the heat from the fissioning fuel in the core passes through 12 outlet nozzles up to the steam-separating drum. The reactor core contains 488 fuel elements, each loaded with 36 round uranium-dioxide fuel rods clad with Zircaloy-2. A core loading of 60 tons of slightly enriched uranium is expected to last about six years, when full reactor efficiency has been attained. The control rods and instrument nozzles are located in corners between the fuel elements. Eighty boron/stainless-steel control rods are provided to control a thermal reactor power of 626,000 kilowatts, for a gross electrical output of 192,000 kilowatts. Net electrical output is 180,000 kilowatts.

### Simplified Flow Diagram

Like the Vallecitos plant, the Dresden station utilizes dual-cycle operation: steam is obtained from two sources, the steam drum and the steam generators. As shown in Fig. 4-22, a mixture of boiling water and steam from the reactor rises to the steam drum (boiler), from which the primary steam is sent to the turbine. After separation from the steam, the water is pumped back to the reactor through four steam generators, one of which is shown in the diagram.

The secondary steam generators produce steam at slightly under 500°F, and this steam is fed to the turbine at an intermediate pressure stage. After giving up its energy to the turbine, the steam is passed through a condenser, where it is converted back to water. Part of the condensed water is pumped

## NUCLEAR ENERGY AND POWER REACTORS

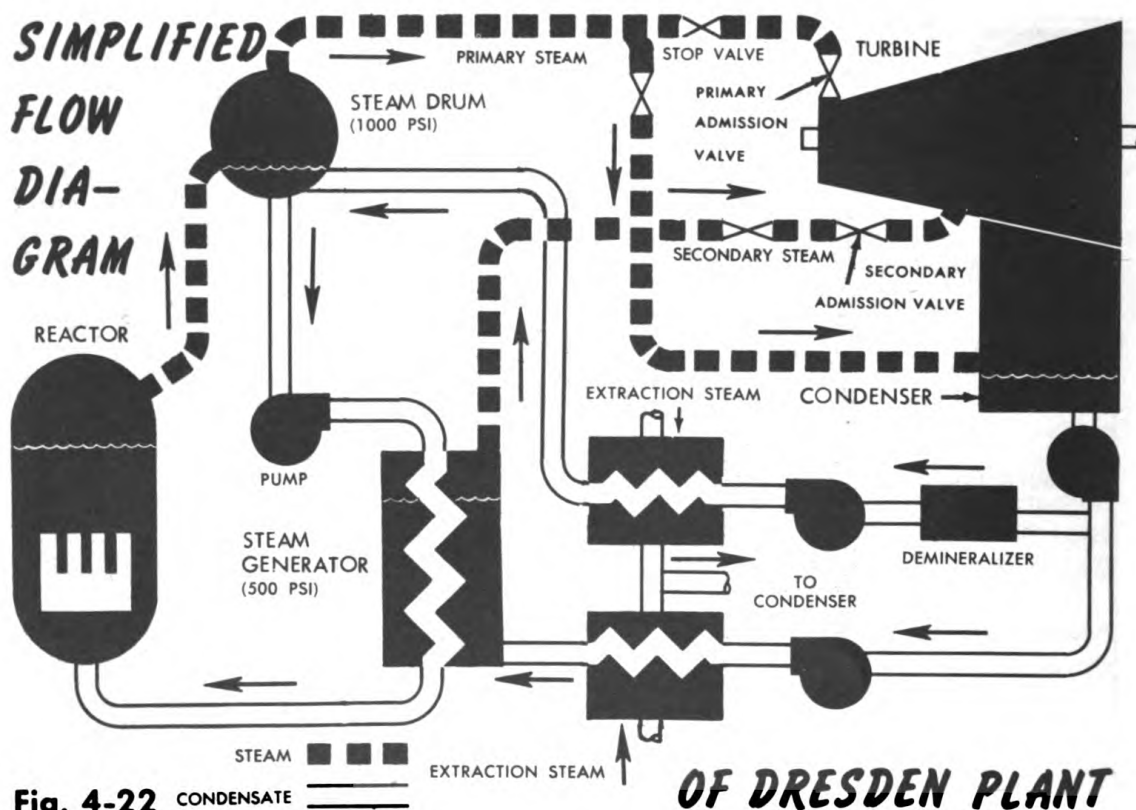


**Fig. 4-21**

back to the reactor through the steam drum and the steam generators; the remainder is again evaporated to secondary steam in the four steam generators.

## NUCLEAR ENERGY AND POWER REACTORS

The dual-cycle feature provides self-regulating reactor control that responds rapidly to changes in power demand. Reactor power is regulated by controlling the temperature of the water returning to the reactor from the steam generators. With a decreasing load, the steam generators produce less secondary steam, which increases the temperature of the water returning to the reactor. The increase in temperature, in turn, slows down the rate of fission and causes the reactor power level to drop. As a result, the steam pressure in the secondary system drops with the declining load. The reverse process takes place with an increasing load.



**Fig. 4-22** OF DRESDEN PLANT

The pressure in the reactor is normally held constant by the turbine's primary admission valve which controls the flow of primary steam. The self-regulating feature varies the pressure in the secondary system in accordance with the load. Load changes cause the turbine's governor to actuate the secondary admission valve for secondary-steam admission.

### Sodium-Graphite Reactors

Radioactive liquids under pressure flowing through a reactor core are potentially dangerous. The sodium-graphite reactor eliminates this danger by using low-pressure liquid sodium as reactor coolant. (Sodium is a metal that has excellent heat conducting properties and remains a liquid at the

## POWER REACTORS AND PLANTS

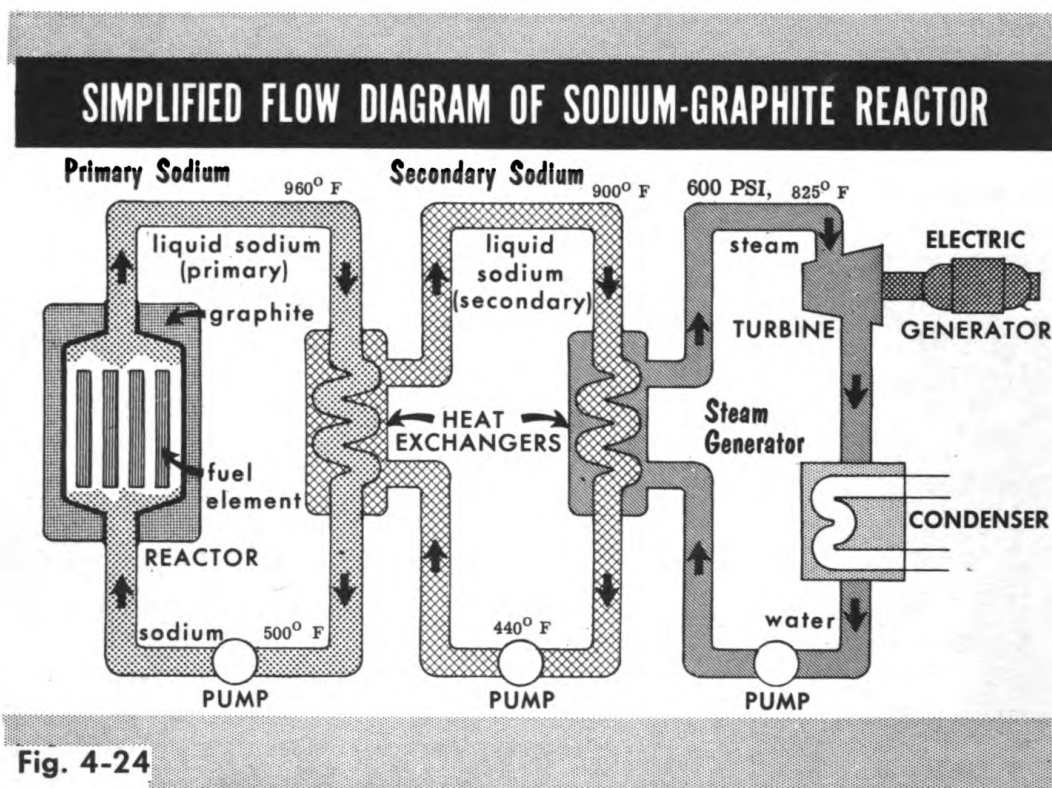
high reactor temperatures.) The reactor itself uses slightly enriched uranium fuel and is graphite-moderated. The major operating unit of this type is a 6500-kilowatt generating plant, (Fig. 4-23), developed for the A.E.C. by North American Aviation, Inc. and operating since April 1957 in the Santa Susana Mountains near Los Angeles, Cal.



As is apparent from Fig. 4-24, the sodium-graphite reactor has two liquid sodium cooling cycles and a steam generating cycle. The primary (radioactive) sodium coolant is pumped through the reactor core at the rate of 1300 gallons per minute, entering it at a temperature of  $500^{\circ}\text{F}$  and leaving at  $960^{\circ}\text{F}$ . The heat from the primary coolant is transferred in a heat exchanger to a secondary liquid-sodium circuit, operating at the same flow rate between inlet and outlet temperatures of  $440^{\circ}\text{F}$  and  $900^{\circ}\text{F}$ , respectively. Water circulating through a heat exchanger-steam generator is brought to a boil by this secondary sodium cycle and the resulting high-pressure (600 pounds per square inch) steam operates the turbogenerator in the familiar cycle. The heat output of this system is 20,000 kilowatts and the electrical output from the generator is 6500 kilowatts. There is also an auxiliary 1000-kilowatt cooling circuit (not shown), which permits cooling after shutdowns.

The core of the sodium-graphite reactor (Fig. 4-25) is a 6-foot  $\times$  6-foot polygon, formed by hexagonal graphite columns, each clad with zirconium. Some of these columns are solid graphite, but most are penetrated axially by a zirconium tube that forms the fuel channel. Each 6-foot fuel element

## NUCLEAR ENERGY AND POWER REACTORS



consists of 7 rods of metallic uranium slugs, sealed in a stainless-steel tube. Seventeen positions are provided in the spaces between the graphite columns to receive experimental samples and the control rods. There are four regulating and four safety rods, each consisting of a column of boron-nickel rings assembled on a tube that is moved in a stainless-steel thimble. The thimbles also contain the drive mechanism for operating the rods. A 2-foot-thick graphite reflector (inner liner) surrounds the entire core.

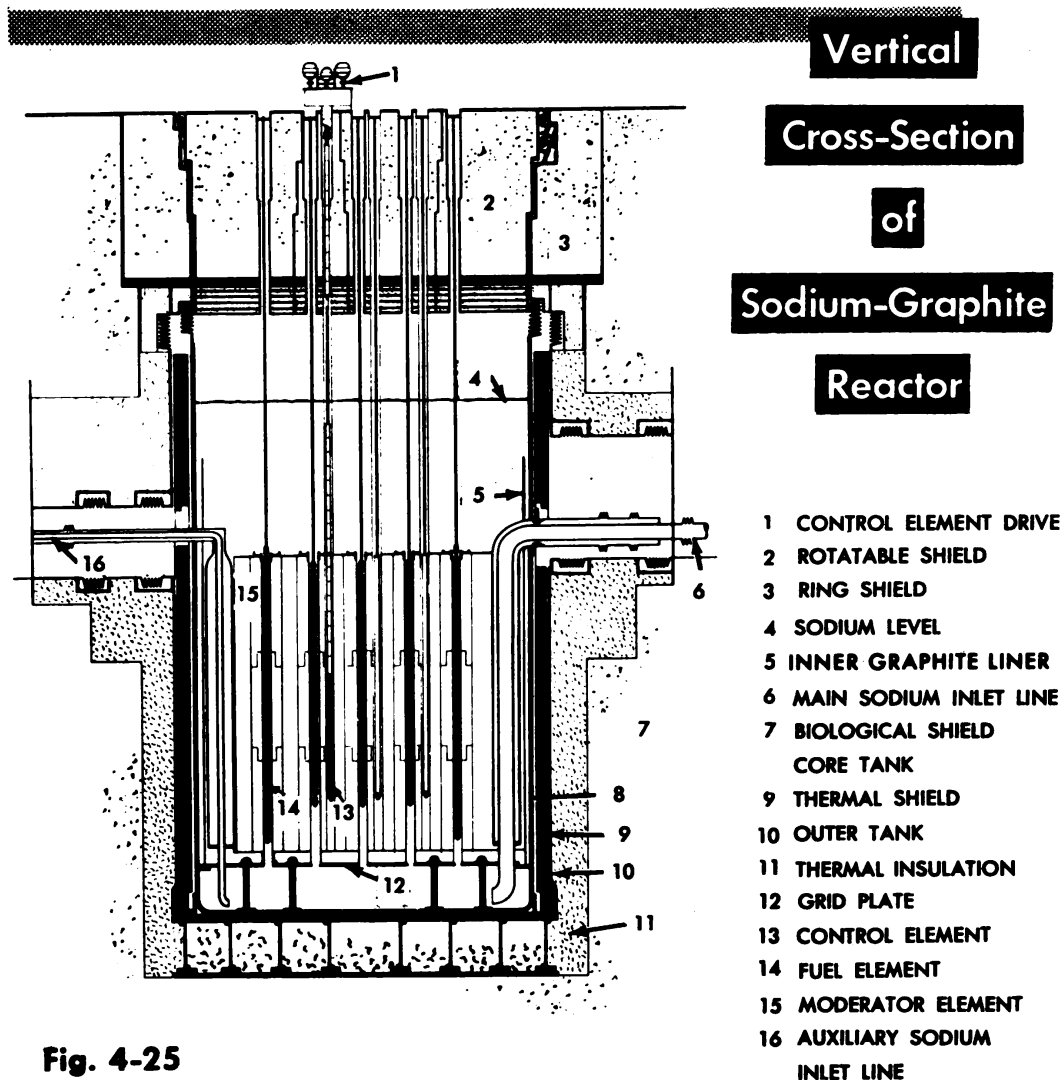
The core assembly is contained in a stainless steel tank, which is surrounded on the sides by a thermal shield of  $5\frac{1}{2}$  inches of steel. The thermal shield on top of the reactor vessel consists of 13 spaced stainless-steel plates, followed by 1 inch of solid stainless steel and a  $1\frac{1}{4}$ -inch layer of lead. A *biological shield* of dense magnetite concrete encloses the reactor.

The cost of the sodium-graphite reactor installation is approximately \$10,000,000. Its major drawback is that the liquid sodium becomes highly radioactive, which causes serious corrosion problems and makes it difficult to preserve the fuel elements for any length of time. Also, in the event of a leak, the sodium would react very violently with water.

### Hallam Nuclear Power Facility

Based on the information developed in operating the Santa Susana sodium reactor installation, a 75,000 kilowatt sodium graphite reactor is being con-

## POWER REACTORS AND PLANTS



**Fig. 4-25**

structed at Hallam, Nebraska, by Atomics International under contract with the Atomic Energy Commission and the Consumers Public Power District of Nebraska. Like all sodium reactors, the Hallam reactor design has the chief advantage of providing high temperature conditions without attendant high pressures on the primary sodium coolant. With sodium heated to about 945°F, the plant is expected to have good steam conditions at the turbine and high overall thermal efficiency. The bugaboo of any such plant, however, is the high radioactivity of the sodium that passes through the reactor and the steam generators. To prevent the radioactive sodium from reacting chemically with the water in the steam system (in the event of a steam generator leak) a secondary, nonradioactive sodium cycle is interposed between the primary (reactor) system and the steam system. Nuclear operation of the Hallam plant is anticipated in 1962.

## NUCLEAR ENERGY AND POWER REACTORS

As shown in Fig. 4-26, the Hallam reactor will be underground. The core is in a stainless steel tank, about 28 feet high and 17 feet in outer diameter. Cast steel,  $7\frac{1}{2}$  inches thick, will serve as thermal shield and 6-foot-thick concrete as biological shield.

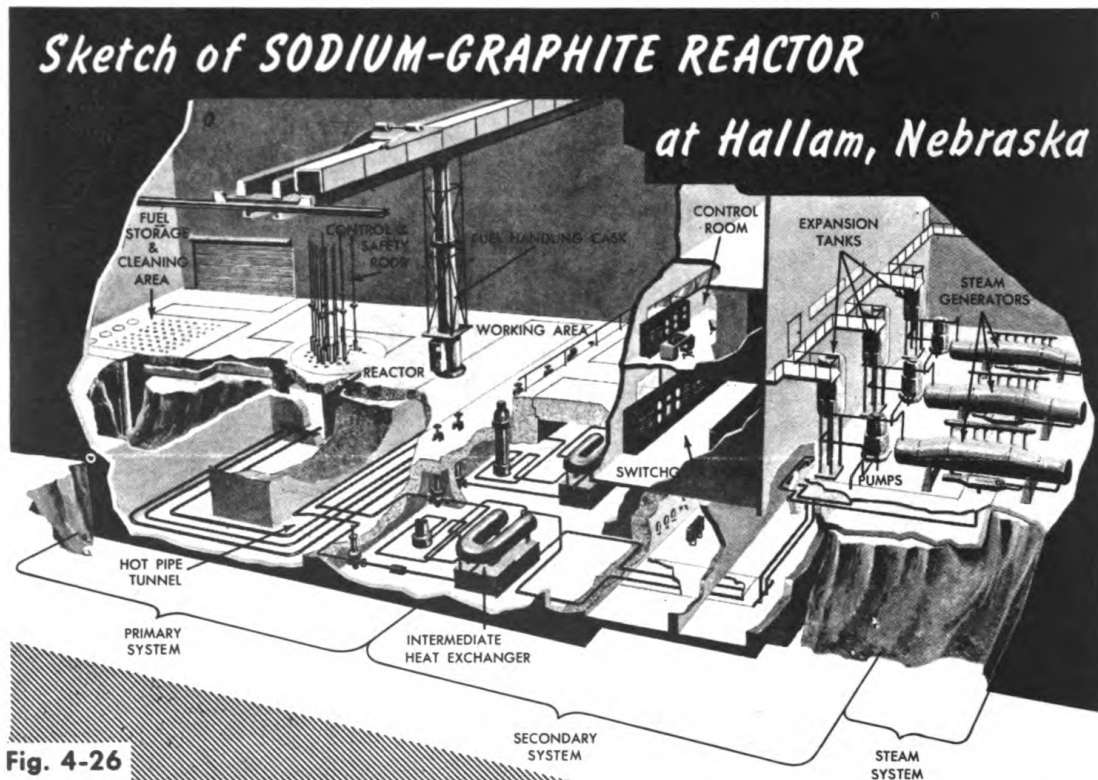


Fig. 4-26

Heat is carried from the reactor by the primary sodium through three separate, parallel loops of piping pumps to the intermediate heat exchangers, where the heat is given up to the secondary sodium system. The primary (radioactive) sodium is pumped back to the reactor. Each of the loops can transfer one-third of the reactor heat to the heat exchanger. The secondary (nonradioactive) sodium, in turn, gives up its heat to water in the secondary steam generators, one being provided for each loop. The high-pressure steam produced by the steam generators drives the turbine. Radioactive contamination of the secondary sodium by leaking primary sodium is prevented by keeping the pressure in the secondary loops above that in the primary loops. Each complete loop, thus, contains a sodium primary system, a sodium secondary system and a portion of the steam system. The turbine generator and associated equipment are not shown.

The horizontal working area of the reactor is level with the base of a fuel-handling cask. This fuel-handling cask is attached to a self-propelled carriage that rides on rails. By using the cask with its heavy built-in shielding, spent fuel elements may conveniently be removed from the reactor and

## POWER REACTORS AND PLANTS

replaced by new ones. The spent elements are kept in the fuel storage and cleaning area (at left) until their radioactivity decays sufficiently for shipment to a processing plant. Note also the control and safety rods protruding above the reactor into the working area.

### Homogeneous Reactor Experiments (HRE)

As we have noted in the last chapter, homogeneous reactors utilizing a liquid fuel-moderator solution have the great advantage of permitting easy refueling and continuous removal of fission products and other corrosive "ashes." By eliminating the solid fuel elements, which must be replaced frequently because of radiation damage, the operation of a homogeneous reactor becomes relatively inexpensive and, hence, of considerable interest for economic nuclear power production.

The Atomic Energy Commission is conducting two homogeneous reactor experiments at the Oak Ridge National Laboratory. The first, the HRE-1, was operated at Oak Ridge from 1952 to 1954 using a fuel of highly enriched uranyl sulfate in a moderating solution of ordinary water. The experiment demonstrated the excellent safety and stability characteristics of the homogeneous reactor, as well as the expected flexibility and simplicity of fuel handling. Moreover, the inherently large negative temperature coefficient of the reactor results in remarkable nuclear stability. You will remember that this works two ways: it makes the reactor safe against sudden excess reactivity; it automatically regulates reactor power to turbine demand.

Based on the successful HRE-1 experiment, a larger and more powerful homogeneous reactor, HRE-2 (Fig. 4-27), was constructed and placed in

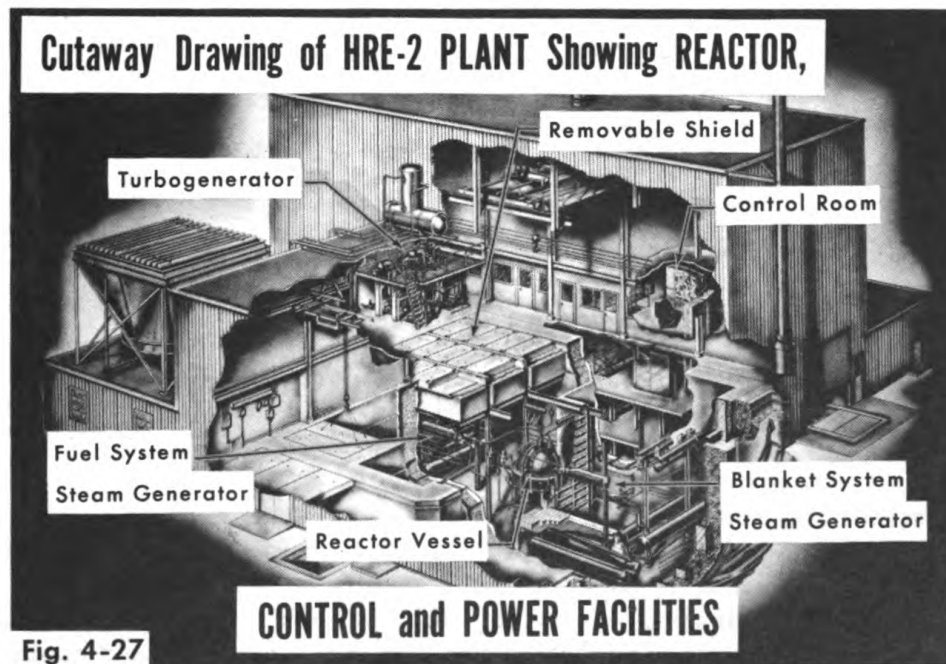


Fig. 4-27

## NUCLEAR ENERGY AND POWER REACTORS

operation at Oak Ridge in December 1957. The design of this reactor eliminates the need for mechanical control rods by making use of the inherent self-regulation of the homogeneous-solution reactor, which also permits continuous removal of the fission products. The enriched uranyl sulfate fuel of the HRE-2 is placed in a heavy-water moderator.

As shown in Fig. 4-28, the HRE-2 is divided into three main systems: the *fuel system*, the *blanket system*, and the *power system*. The uranyl-sulfate

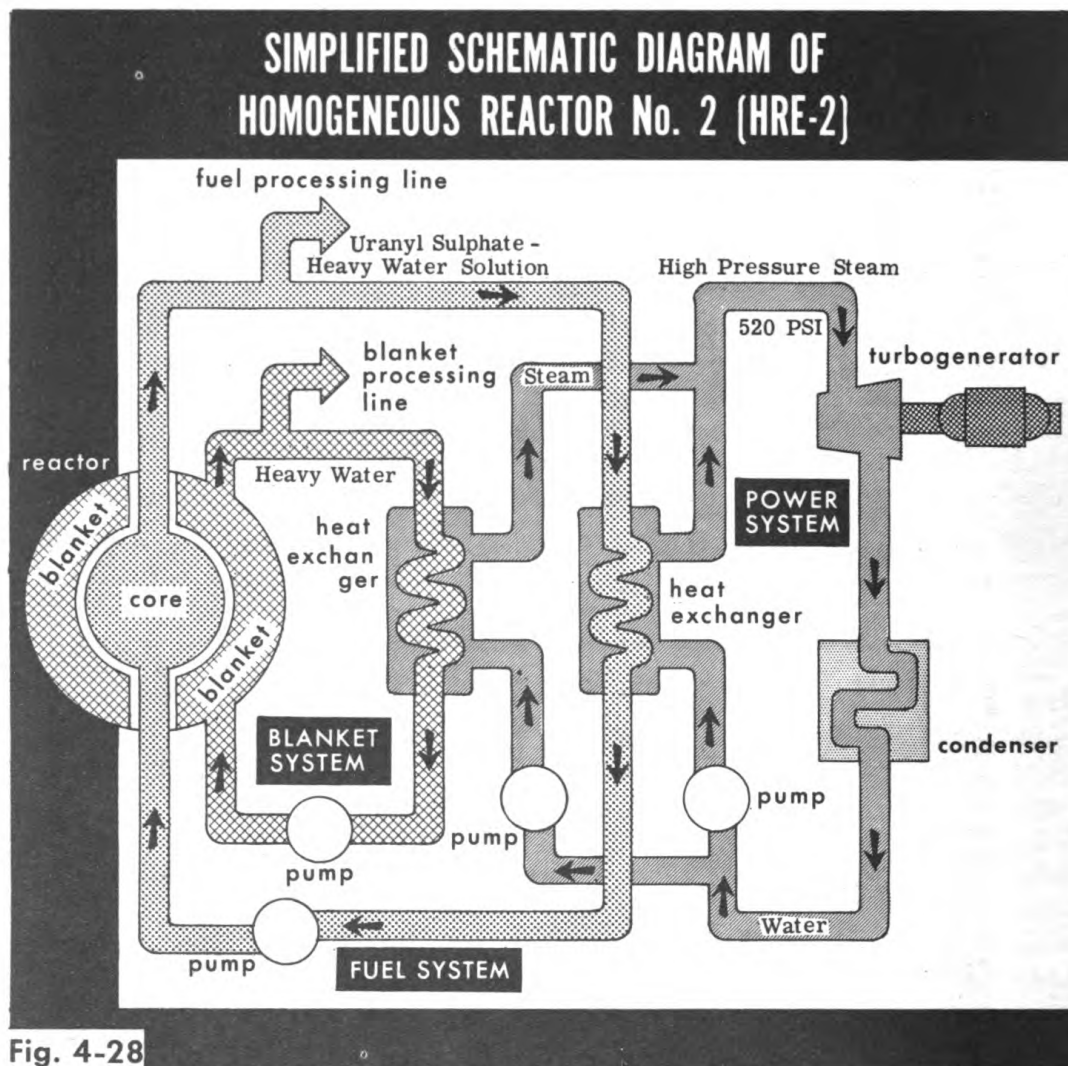


Fig. 4-28

heavy-water fuel solution (enriched by 4 kg of U-235) is pumped under pressure through the reactor core and gives up its heat to ordinary water in a heat exchanger. The water is converted into steam, which is fed into the power system pipes. A blanket, consisting of about 410 gallons (1550 liters) of heavy water, surrounds the reactor core, serving as reflector and coolant. (In

# POWER REACTORS AND PLANTS

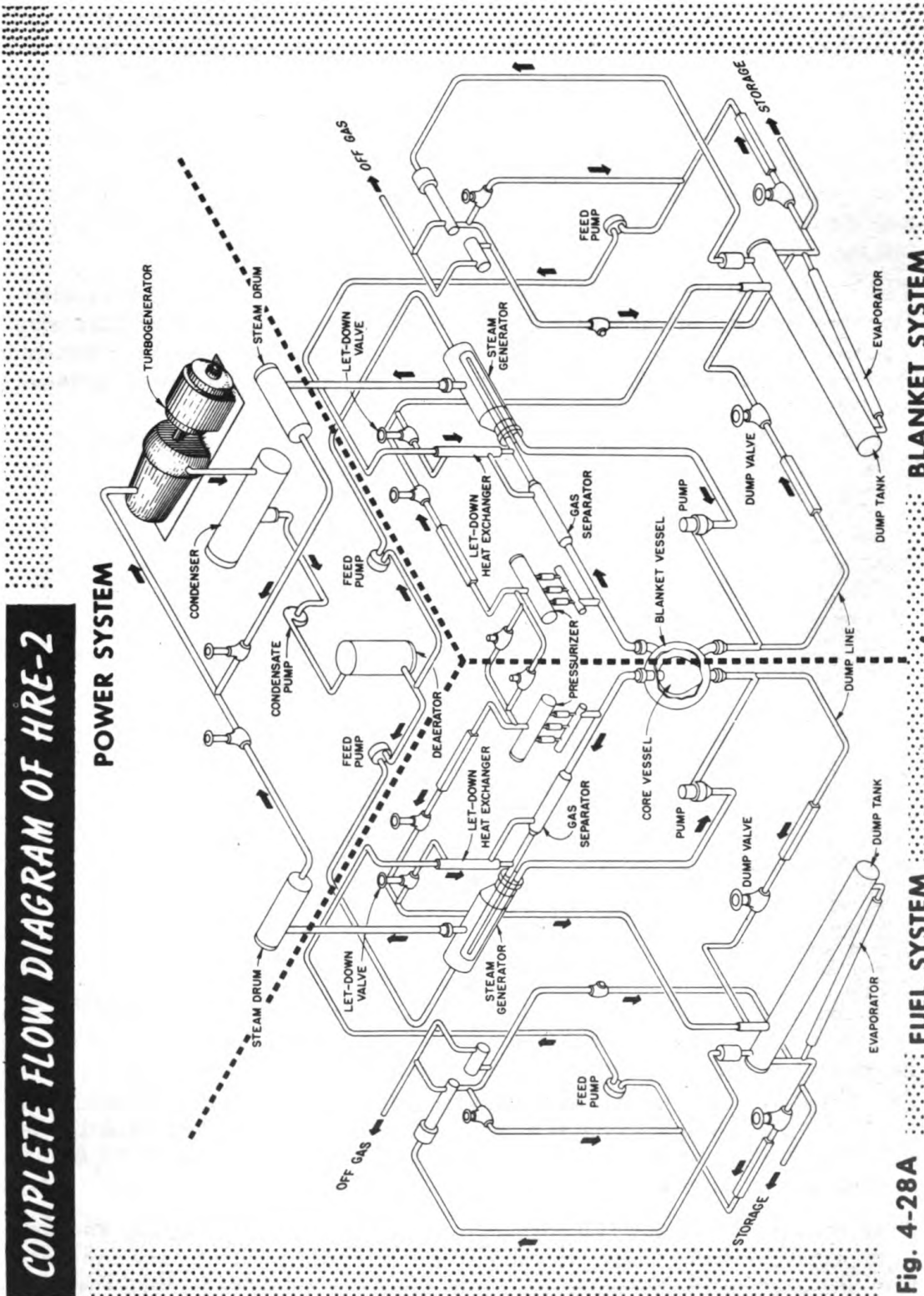
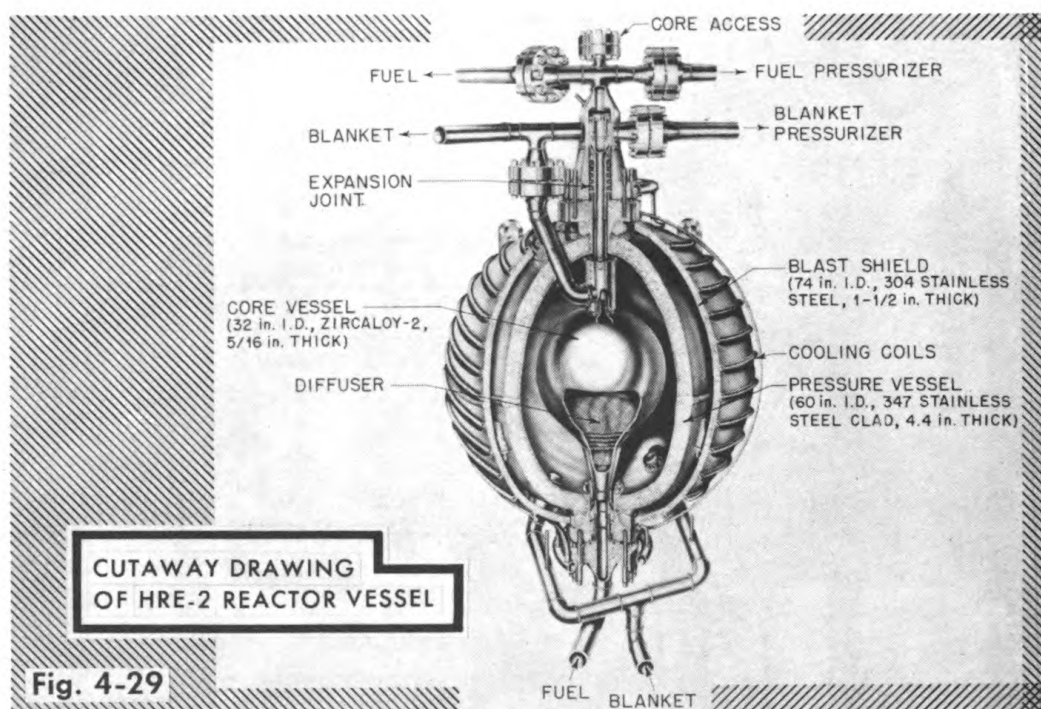


Fig. 4-28A

## NUCLEAR FISSION AND THE CHAIN REACTION

a later phase of the test program, the heavy-water blanket will contain depleted uranyl sulfate in solution.) The heavy-water blanket/coolant is circulated under pressure through another heat exchanger, which again transfers the heat to the water-steam cycle of the power system. The high-pressure steam from *both* heat exchangers (520 pounds per square inch at the heat exchanger) is then used to drive the turbogenerator. After condensation, the water is pumped back to the fuel and blanket systems. Both the fuel and blanket lines are tapped by secondary lines to permit chemical processing and storage.

The reactor structure is quite simple. (See Fig. 4-29.) The fuel solution is contained in a spherical vessel, 32 inches inner diameter, made of "Zircaloy"—a 60-inch (inside diameter) stainless-steel-clad pressure vessel surrounds the core container, the hollow space in between being filled by a 14-inch



heavy-water blanket. The pressure vessel, in turn, is surrounded by a 1½-inch thick stainless steel blast shield, which is cooled on the outside by circular cooling coils. The entire reactor vessel is surrounded by a *thermal neutron shield*, consisting of barytes, sand and water, followed by a heavy steel-and-concrete *biological shield*.

Note the absence of any type of mechanical control rods. Startup and long-term coarse control of reactivity (*shim*) is achieved by varying the concentration of the uranyl sulfate fuel solution, while the negative temperature coefficient is relied upon for safety and fine regulation in accordance with the

## POWER REACTORS AND PLANTS

power demand. These simplifications in structure, fuel handling, operation and maintenance result in a highly economical reactor, that holds promise as a commercial power producer.

### Fast Breeder Reactors

Most reactors convert a certain amount of non-fissionable *fertile* material into fissionable fuel. Reactors using an enriched uranium fuel convert a portion of the fertile U-238 into fissionable plutonium, by the process described in Chap. 2. Similarly, reactors using thorium as a fertile material convert a portion of it into fissionable U-233 in an analogous reaction also discussed in Chap. 2. A *breeder reactor* differs from ordinary reactors in that it is designed to convert more fertile material into fissionable form than the amount of fissionable fuel it consumes. For example, a plutonium breeder converts more U-238 into plutonium than the amount of U-235 it consumes. The advantage of breeding for power reactors is evident, inasmuch as the newly produced fuel can be "burned" along with the original supply to produce greater fuel economy and lower power cost.

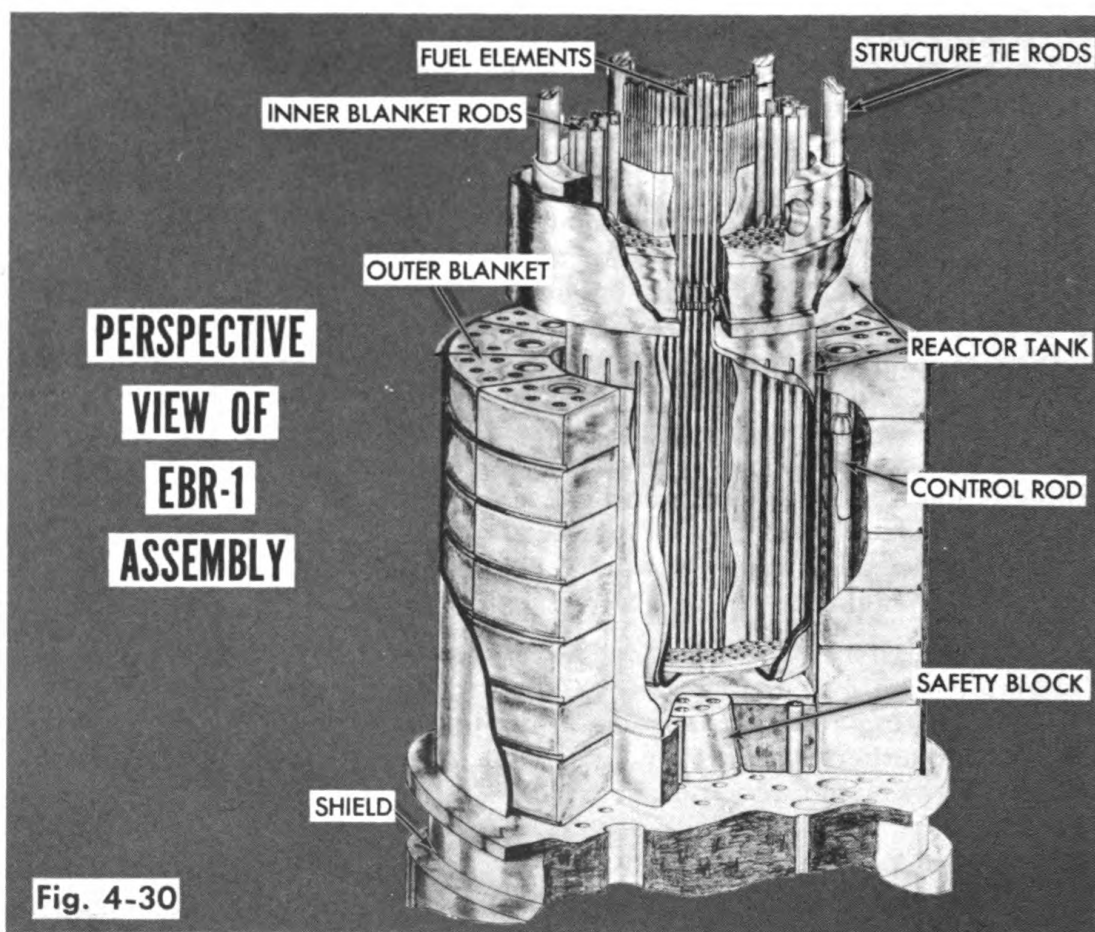
Breeders usually do not use a moderator to slow down the fission neutrons. Operation with fast neutrons results in a more favorable fission-to-capture ratio, permitting a greater uranium-plutonium (or thorium-U<sup>233</sup>) conversion than would otherwise be possible. From a power production viewpoint, therefore, the main interest is centered in *fast breeders*.

### Experimental Breeder Reactor No. 1 (EBR-1)

A small experimental breeder reactor (EBR-1), designed by the Argonne National Laboratory and operating since December 1951 at the National Reactor Test Station in Arco, Idaho, achieved the double distinction of being the first known breeder reactor and also the first reactor to generate useful electric power. The EBR-1 is a fast, unmoderated, enriched-uranium reactor, which attains a heat output of about 1400 kilowatts and an electrical output of 200 kilowatts from a fast neutron flux of about  $1.1 \times 10^{14}$  neutrons cm<sup>2</sup>-sec. Its *specific power* is about 18 kilowatts per kilogram of U-235 and its *power density* about 4 kilowatts per cubic inch of the reactor core, which is far greater than the power density inside a jet engine. The *conversion ratio* of the EBR-1 is 1.01, which means that 1 per cent more fissionable fuel is produced than is used up.

The football-sized core of the EBR-1, which produces most of the heat output is fueled with enriched uranium slugs contained in stainless steel rods. (See Fig. 4-30.) An inner blanket of natural uranium rods is placed above and below the fuel rods and the entire assembly is cooled by a liquid sodium-potassium alloy (NaK). The core and inner blanket are surrounded by an *outer blanket* of natural uranium bricks, which are penetrated by variously-sized holes for air cooling and the insertion of control rods. Most of the fissionable plutonium is produced in the two U-238 blankets, which capture the fast neutrons from the core.

## NUCLEAR FISSION AND THE CHAIN REACTION



As shown in Fig. 4-31, the liquid-sodium/potassium coolant flows by gravity from the supply tank (top center in the illustration) through the inner blanket and reactor core, from which it absorbs heat, and leaves the reactor at a temperature of about 600°F. The primary coolant then enters a heat exchanger, where it gives up the heat to a secondary liquid-sodium/potassium coolant, and flows into a receiving tank. An electromagnetic pump (bottom of illustration) lifts the cooled liquid metal to the elevated supply tank and the primary cycle starts over again.

Since the liquid-sodium/potassium in the primary circuit becomes highly radioactive and it is necessary to limit the amount of equipment that must be shielded, the secondary liquid-sodium/potassium circuit is used. The heated secondary liquid metal is pumped to an explosion-proof steam boiler, where the heat is used to convert water into high-pressure steam. The steam is passed to a conventional 250-kilowatt turbogenerator to generate power and then is condensed and returned to the boiler by a feedwater pump.

The original core of the EBR-1 was damaged in November 1955 during an experiment to determine "runaway behavior" for sudden power increases. In

## POWER REACTORS AND PLANTS

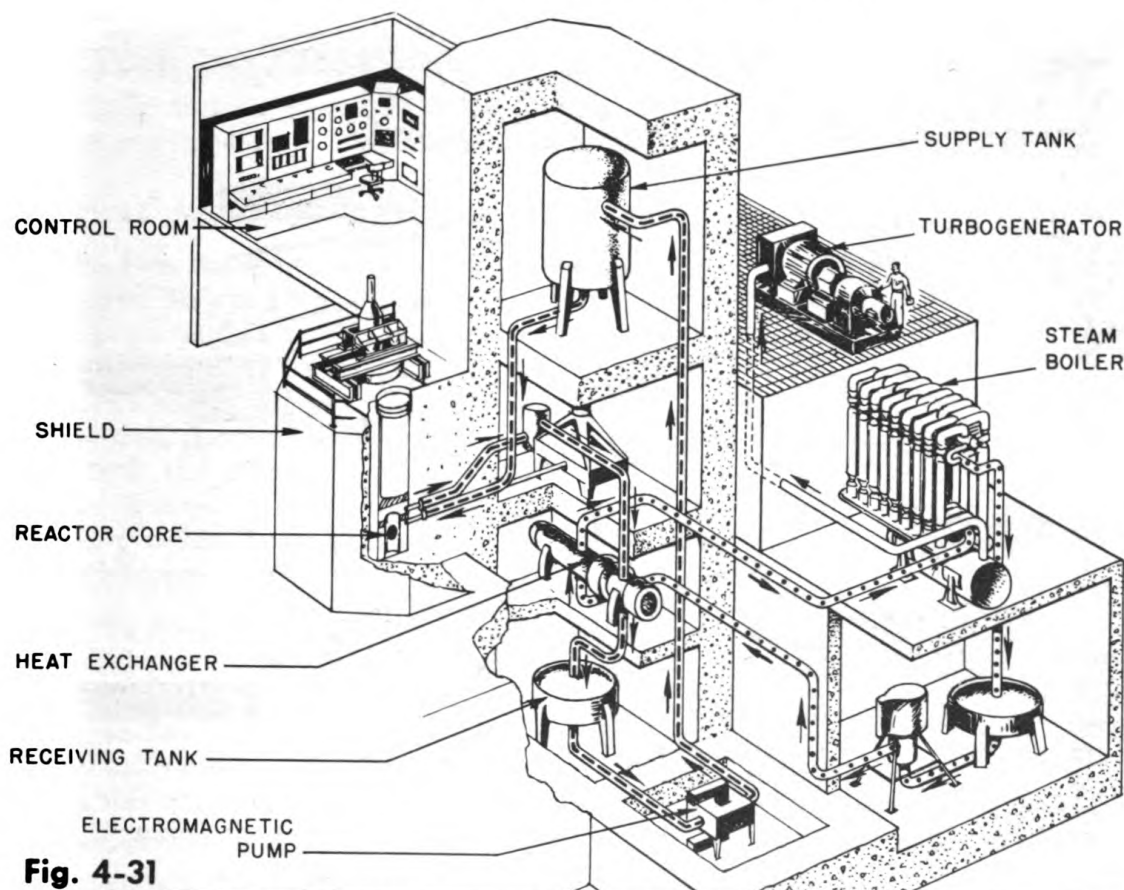


Fig. 4-31

**CUTAWAY DRAWING and FLOW DIAGRAM of EBR-1 INSTALLATION**

November 1957 the reactor was put back in operation with its new Mark III core.

### Experimental Reactor No. 2 (EBR-2)

After the EBR-1 demonstrated the feasibility of breeder power reactors on a small scale, construction on a second power breeder (EBR-2) was started in 1957 and the \$40-million plant (Fig. 4-32) is expected to be in operation in 1959. The EBR-2 will have a large scale-up in power, the design providing for a heat output of 62,500 kilowatts and an electrical output of 20,000 kilowatts, with a specific power of about 300 kilowatts per kilogram of U-235. Like the EBR-1, it is an unmoderated, enriched-uranium-plutonium, heterogeneous reactor. Its core is designed more efficiently, however, to make maximum use of fast neutrons for transmuting uranium-238 into plutonium. This is accomplished by placing a large number of *pin-type* enriched uranium or plutonium fuel elements into hexagonal tubes and surrounding them first with an inner blanket of stabilized uranium pin elements and then an outer blanket of uranium prisms in a radiator-type arrangement. Both

# NUCLEAR ENERGY AND POWER REACTORS

## CUTAWAY VIEW OF EBR-2 PLANT

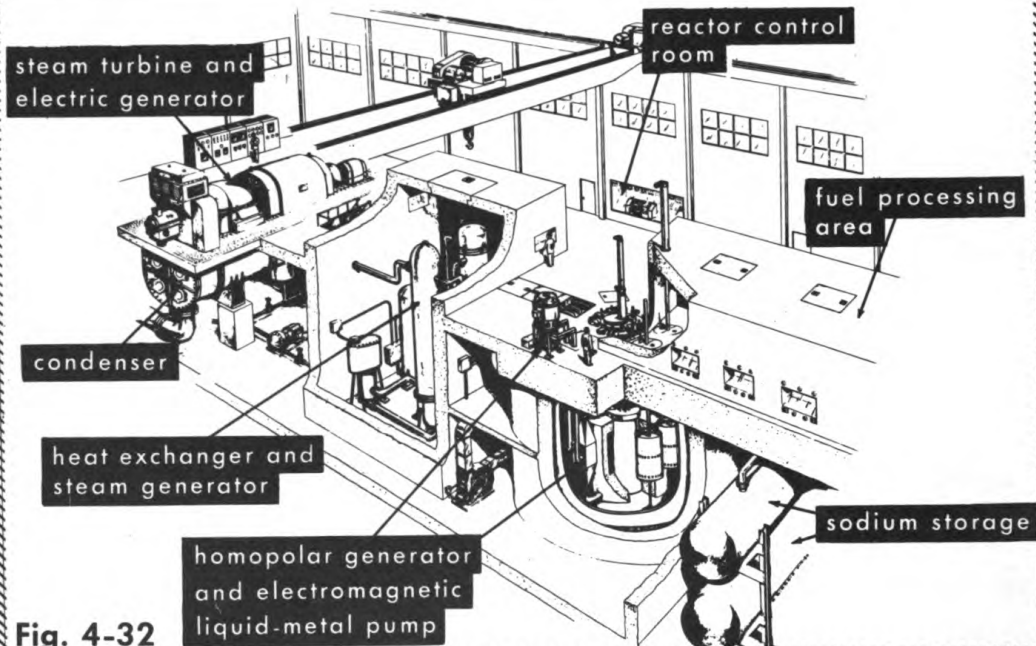
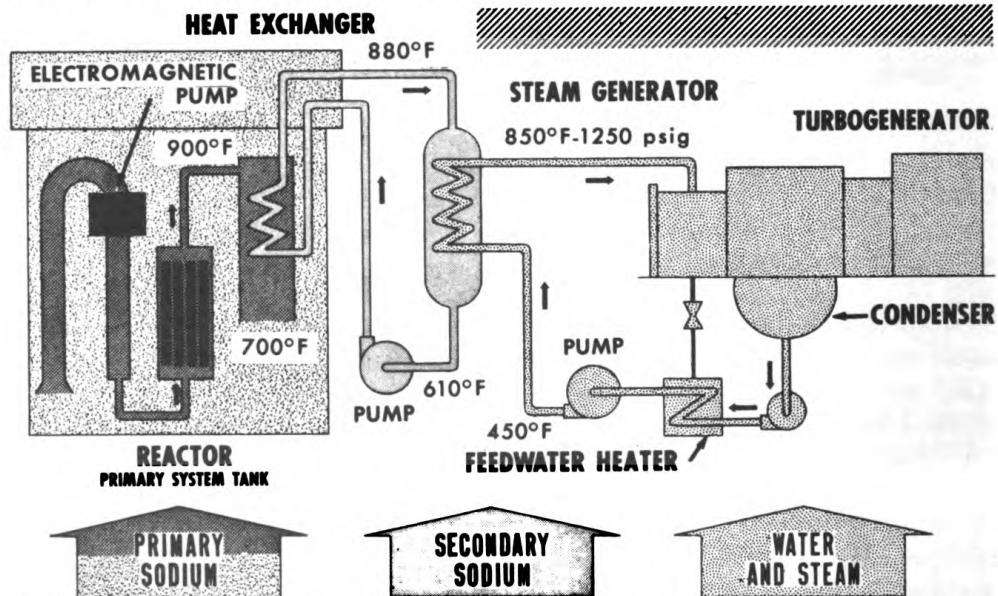


Fig. 4-32



## FLOW DIAGRAM OF EBR-2

(EXPERIMENTAL BREEDER No. 2)

Fig. 4-33

## POWER REACTORS AND PLANTS

the primary (reactor) and secondary coolants in the EBR-2 are *liquid sodium*, rather than a sodium/potassium alloy. The primary sodium, secondary sodium, and water-steam cycles of the EBR-2 are essentially similar to the dual cycle described for the EBR-1, as shown in Fig. 4--33.

### Enrico Fermi Atomic Power Plant

Based on the experience with fast breeders at Argonne and Los Alamos, the Atomic Power Development Associates, Inc. are designing a full-scale heterogeneous fast breeder with a net electrical capacity of 90,000 kilowatts for the non-profit Power Reactor Development Company, an association of 21 electrical utility firms. Construction on the Enrico Fermi reactor plant at Lagoona Beach, Mich., was started in 1956, and at its scheduled completion in 1960, the plant will feed electrical power into the Detroit Edison system. The Atomic Energy Commission under its power demonstration program will provide financial research and development assistance and waive fuel use charges for five years.

In the Fermi plant, a gastight cylindrical steel reactor building houses the reactor, fuel handling mechanism and the intermediate heat exchangers, sodium pumps, piping and storage tanks of the primary system. The building is fabricated of 1-inch thick steel plate, capable of containing fission products and radioactive sodium released in the event of a reactor accident. To minimize the chances of a chemical reaction between the oxygen and water vapor in the air and the sodium, the air in the reactor building is dehumidified and reduced in oxygen content in the reactor proper.

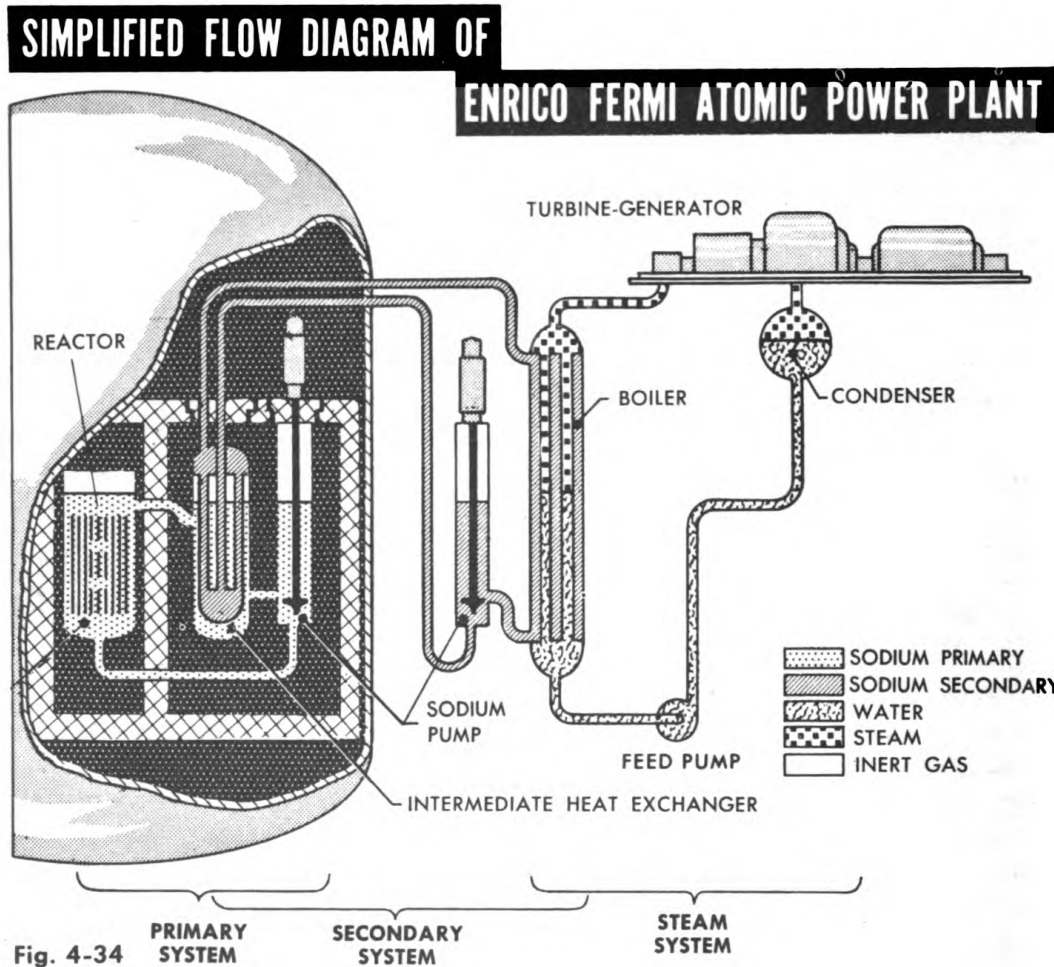
The reactor is enclosed by the reactor vessel, which is itself surrounded by the primary shield tank. This tank provides additional containment for the sodium in the event of a reactor vessel leak and supports the primary neutron shield. The Fermi reactor is small in size, since its core contains only 485 kilograms of highly (27%) enriched uranium and no moderator. The 91 fuel elements of the reactor core are surrounded by 572 radial blanket elements which contain fertile uranium that has been depleted in its uranium-235 content. In addition, each fuel element has two axial blanket sections near its ends, also containing depleted uranium. The greater part of the reactor heat—some 300 megawatts thermal output—is generated in the enriched uranium core, while fissionable plutonium is produced in the surrounding breeder blanket. Reactor control is accomplished by two shim control rods, with eight additional rods provided for safety. The gross electrical output of the generator is 100,000 kilowatts.

The fuel-handling setup is similar to that at the Hallam plant. Fuel enters the reactor building and reactor in a shielded transfer-cask car and is received by the fuel-handling mechanism incorporated into the reactor. The fuel handling mechanism also transfers spent fuel to the car for removal to an area outside of the building, where it is cleaned of sodium and stored until its radioactivity has decayed sufficiently for shipment.

## NUCLEAR ENERGY AND POWER REACTORS

### Simplified Flow Diagram

The simplified flow diagram of the Fermi plant (Fig. 4-34) shows one of the three circuits whose job it is to generate the steam that transfers heat from the reactor to three boilers which in turn drives the turbine. In the primary



coolant system, hot radioactive sodium is circulated by a pump from the reactor to the intermediate heat exchangers and back to the reactor at a pressure of 92 pounds per square inch. The intermediate heat exchangers transfer the heat from the radioactive sodium to the nonradioactive sodium of the secondary system. This system includes the tube side of the intermediate heat exchangers, the shell side of the boilers, centrifugal pumps, piping and auxiliary equipment. The intermediate loop operates at a low average pressure of 30 pounds per square inch.

The steam power-generating system, consisting of three boilers (only one is shown), turbine-generator, condenser, pumps and piping, is shown at right

## POWER REACTORS AND PLANTS

of the flow diagram. Each steam generator is capable of producing about 500,000 pounds of steam per hour under a pressure in excess of 1000 pounds per square inch (on the water side) and of a temperature of about 780° F. The steam passes through the turbine and is returned to the liquid state by the condenser equipment and three regenerative cycles (not shown). De-aerating equipment processes the hot pressurized water and the boiler feed pump returns the water to the steam generators, where the cycle is repeated.

### Organic Moderated Reactors

Let us now take a glimpse at some speculative ventures in the recently expanded nuclear power development program of the Atomic Energy Commission. The first of these is an *organic-moderated and cooled reactor*. Research on organic-moderated and cooled reactors and on a variety of organic liquids has been carried on for a number of years. Any one of a number of polyphenyls can serve as organic moderator and coolant. In practice, a commercially available mixture of terphenyls is presently used.

Organic-moderated and cooled reactors have many of the advantages of pressurized water systems and, in addition, those provided by the organic coolant-moderator. Among these advantages are low system pressure, the elimination of hazardous chemical reactions with uranium or water, negligible corrosion of ordinary construction materials, and low induced radioactivity in the primary coolant.

A possible drawback is polymerization or decomposition of the organic liquid. Among the variety of organic liquids tested for stability, certain polyphenyls, including diphenyl and terphenyl, have been found most stable under the thermal and radiation conditions prevailing during reactor operation. Slight decomposition (polymerization) of these organic liquids does occur, however. In organic-moderated power reactors this problem is controlled by incorporating a purification system in the heat-transfer circuit and by continuous addition of small amounts of makeup fluid to replace the polymer removed by decomposition.

### Organic-Moderated Reactor Experiment (OMRE)

A reactor that uses the hydrocarbon terphenyl as both moderator and coolant has been in operation since September 1957 at the National Reactor Testing Station in Arco, Idaho. The OMRE reactor is designed for a heat output of 5000 to 16,000 kilowatts, but no attempt is made at this time to extract useful electrical power from the reactor. The experiment is primarily designed to simulate the conditions of heat transfer, temperature and coolant flow that may be encountered in later, practical power reactor versions. The high boiling point of the organic coolant makes possible a high-temperature/low-pressure system, along with the other advantages of organic liquids we have mentioned.

## POWER REACTORS AND PLANTS

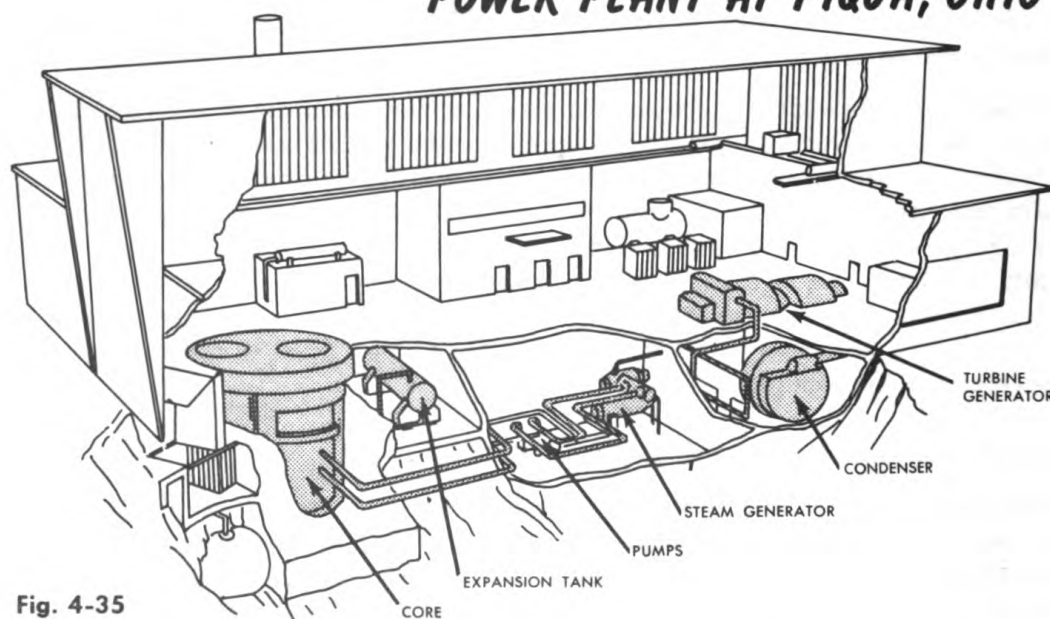
The OMRE core is fueled with uranium, enriched with 20.6 kilograms of U-235, and uses terphenyl as coolant, moderator and reflector. Control is obtained by 12 boron-carbide control rods, operated by a rack-and-pinion drive. OMRE is presently used to investigate a number of problems, such as potential fire and explosion hazards and the rate of decomposition of the organic moderator-coolant.

### Piqua Organic Moderated Reactor Power Plant

The city of Piqua, Ohio, has submitted a proposal for an organic-moderated and cooled reactor plant, which will be constructed if the OMRE installation at Arco, Idaho, bears out the validity of the organic moderated reactor concept, and if a satisfactory fuel element can be developed. The latter task is entrusted to Atomics International, Inc., under contract with the Atomic Energy Commission. Plans call for operation to commence in 1961.

Figure 4-35 shows the chief components of the proposed plant. The system consists of a closed loop in which a mixture of terphenyls serving as moderator and coolant carries heat from the reactor to a steam generator or boiler,

### **PROPOSED ORGANIC-MODERATED REACTOR POWER PLANT AT PIQUA, OHIO**



which produces the steam required to drive the turbine. A rated thermal heat output of 45,500 kilowatts and an electrical output of 12,500 kilowatts is planned. Steam would be produced at 415 pounds per square inch and 550°F. The negative temperature coefficient of the organic-moderated reactor will act as a governor to limit power surges and excess power levels.

## NUCLEAR ENERGY AND POWER REACTORS

Furthermore, the nuclear characteristics permit a compact core with good neutron economy. The entire heat-transfer system should be relatively accessible because the organic coolant becomes only slightly radioactive.

The reactor core for the Piqua plant will be in a steel reactor tank below ground level. Inside the reactor tank a thin-walled core tank contains the liquid organic moderator and the core. The core will consist of 138 fuel elements and 8 control and safety rods, immersed in the organic liquid. Fuel elements suspended from a top grid plate are enclosed in steel boxes which extend through a bottom grid plate. A Piqua fuel element consists of 10 flat fuel-bearing plates and two aluminum end plates, held together by aluminum side plates. Each fuel plate will contain uranium metal enriched up to 1.8% in U-235. A core loading will require 6250 kilograms of the enriched uranium. For an 80% plant factor, the fuel replacement rate should be about 330 kilograms of uranium per month, equivalent to 73 fuel plates or 7.3 fuel elements. At this rate, a core loading should last approximately 18 months.

Control rods will be driven by geared electric motors, located in the control rod drive room. The rods are neutron-absorbing, boron-steel rings, mounted on steel tubes. In general, all materials in the reactor core and primary coolant system will be chemically compatible. The potential energy stored in the system, in the form of gases or liquids under pressure, will be small, the operating pressure being only 65 pounds per square inch gage.

### Piqua Flow Diagram

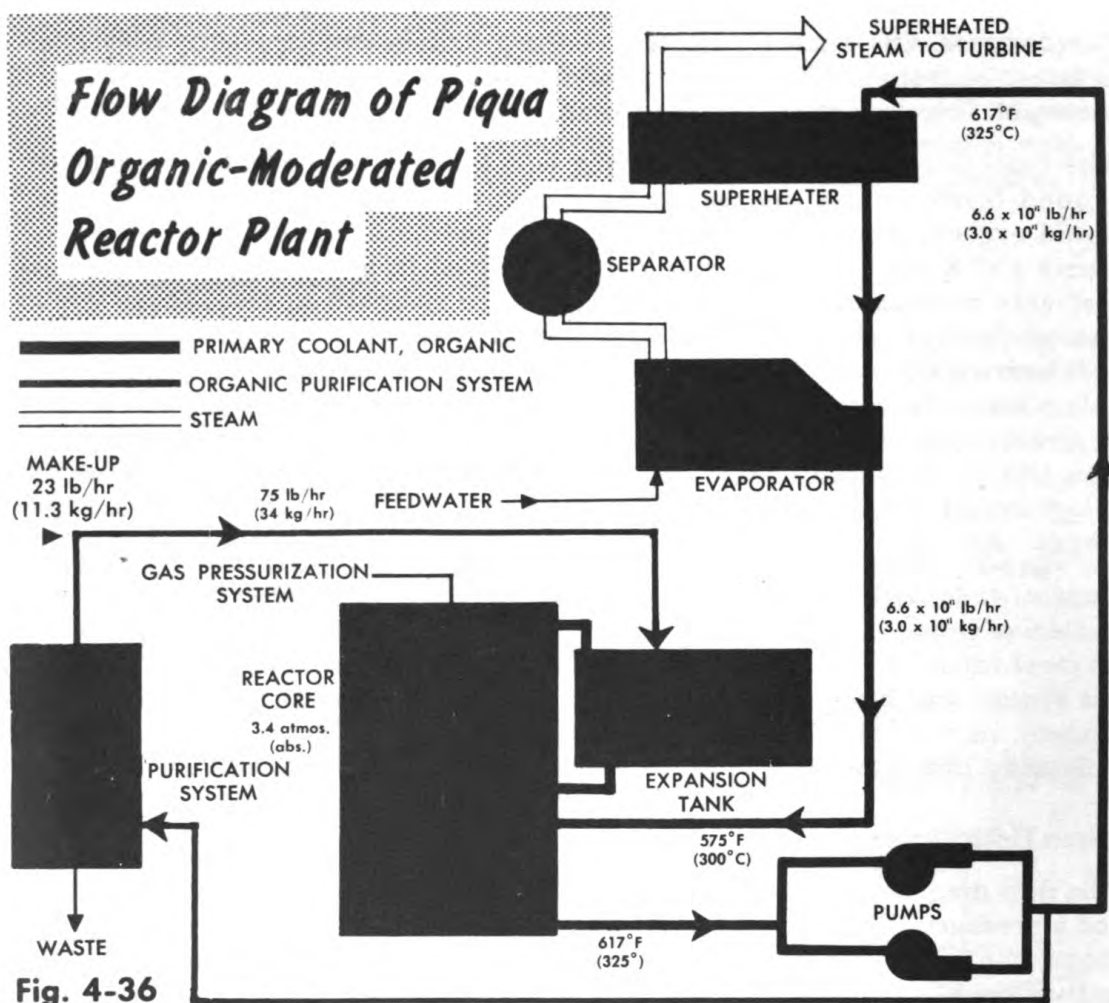
The flow diagram for the Piqua plant (Fig. 4-36) is essentially similar to that for a pressurized water reactor. The heat-transfer system is laid out in two loops, one being shown on the diagram. Each loop is enclosed in an individually shielded vault, located next to the reactor tank below ground level. By use of isolating valves, maintenance work can be done on one loop without plant shutdown.

The estimated polymerization rate of the organic terphenyl coolant at the reactor outlet temperature of 617°F is 0.5 pounds per thermal megawatt-hour of reactor operation. A purification system is tapped into the main coolant piping to replenish the coolant at this rate. Used terphenyl continuously passes through the purification system at about 75 pounds per hour. After the polymers are removed in a packaged-column fractionating still, the purifier terphenyl is condensed, pumped to an accumulator tank, and then returned to the main coolant streams. Sufficient make-up of new terphenyl is added from the "new coolant" storage tank to maintain a constant level in the reactor tank. The purification system is enclosed in a shielded vault.

### Liquid Metal Fuel Reactor Experiment (LMFRE)

Reactors using *liquid metal as a fuel* are technically feasible and appear attractive from a cost standpoint. Research and development on an experimental liquid-metal-fueled reactor (LMFRE) is now in progress, but for the

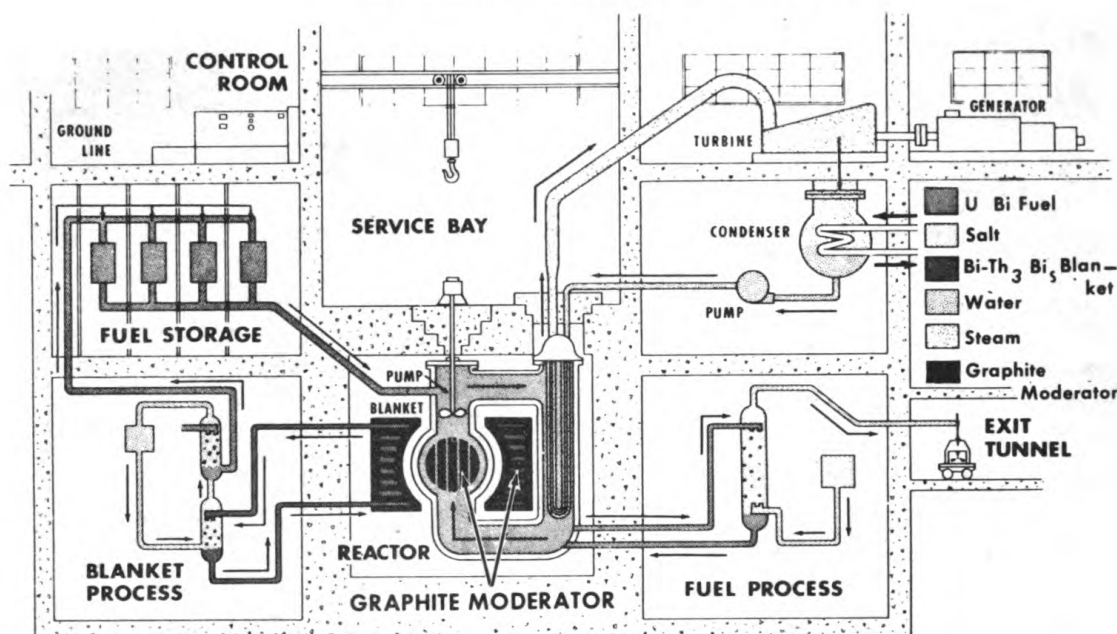
## NUCLEAR ENERGY AND POWER REACTORS



present a reference design (LMFR) is used for comparative analysis. This design is based upon a 550 megawatt thermal reactor, fueled by a solution of fissionable U-233 in molten bismuth. The fuel is surrounded by a blanket consisting of a slurry of fine thorium-bismuthide particles in liquid bismuth, which permits the breeding of U-233 fuel. A graphite core serves as moderator.

As shown in Fig. 4-37, the U<sup>233</sup>-bismuth fuel is pumped through the core of the reactor, which generates 90% of the heat. The heated fuel is then passed through a heat exchanger, where it gives up its heat to transform water into steam (2000 pounds per square inch), which drives the turbogenerator. The cooled fuel is recirculated to the bottom of the core. On-site processing of the fuel would involve continuous removal of all fission products. Another chemical process removes both the fission products and new fuel from the blanket material. Various studies are in progress at present to determine the nuclear stability of the reactor and establish the metallurgical resistance of the construction materials.

## POWER REACTORS AND PLANTS



### FLOW DIAGRAM for PROPOSED LIQUID-METAL-FUELED REACTOR INSTALLATION (LMFR)

Fig. 4-37

#### Los Alamos Molten-Plutonium Reactor Experiment (LAMPRE)

In 1955 the Los Alamos Scientific Laboratory initiated research and development on a homogeneous, fast (non-breeding) reactor, to be fueled with molten plutonium metal. This reactor, known as LAMPRE-1, will produce about 1 megawatt (1000 kilowatts) of heat and is expected to be critical in 1960. A more advanced reactor prototype, LAMPRE-2, is to follow later on, if the first reactor proves successful, and for the final phase an electric-power-producing molten-plutonium reactor, LAMPRE-3, is planned.

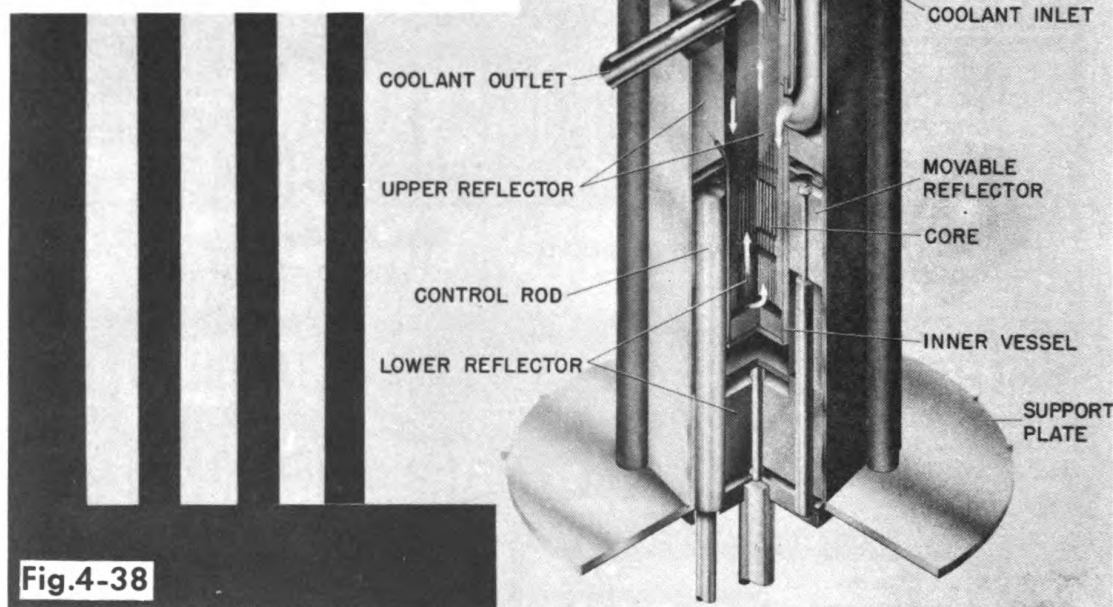
The LAMPRE-1 reactor core (Fig. 4-38) will consist of a  $6 \times 6$ -inch right cylinder containing molten plutonium alloy fuel in the spaces between sodium coolant tubes. A nickel blanket will surround the core, serving as fast neutron reflector. This nickel reflector will be movable for regulating the reactor power, thus eliminating control rods. The reactor is to operate at a temperature of  $650^{\circ}\text{C}$ , attaining a specific power of 70 kilowatts per kilogram of fuel.

#### Other Experimental Reactors

In addition to the experimental reactors just described, the A.E.C. is plan-

## NUCLEAR ENERGY AND POWER REACTORS

### ARTIST'S CONCEPTION OF LOS ALAMOS MOLTEN-PLUTONIUM REACTOR (LAMPRE)



ning other experimental types in its program. These projects will include among others, a *gas-cooled high-temperature reactor* and a *dual-purpose plutonium recycle reactor*, capable of producing both electrical power and plutonium for weapons. These are part of a five-year program, calling for an annual expense of about \$200 million to be spent on the development of power-producing reactors.

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